Report 14354-M-8

HYDROGEN-OXYGEN HIGH P_c APS ENGINES

NAS 3-14354

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AEROJET LIQUID ROCKET COMPANY

SACRAMENTO, CALIFORNIA • A DIVISION OF AEROJET-GENERAL

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FOREWORD

The purpose of this contract is the development of a comprehensive technology base for high performance, long life, gaseous hydrogen-gaseous oxygen rocket engines suitable for the Space Shuttle APS. Significant goals in thruster design are a 50-hour firing life over a 10-year period, with up to 10^6 restarts, and single firings up to 1000 sec.

The program was initially structured as two parallel efforts: one directed toward high pressure (100 to 500 psia) systems and the other toward low pressure (10 to 20 psia) systems. Nominal engine thrust in each case is 1500 lb. Initial program tasks were devoted to the analytical evaluation and screening of injector and cooled thrust chamber concepts for both pressure levels. This was followed by closely paralleled but separate experimental evaluations of low and high pressure injectors and ignition devices. Recommendations of specific injector and igniter designs have been made for both pressure levels as a result of these tests.

As these parallel efforts were about to enter the cooled chamber fabrication phase, the program was redirected to apply additional emphasis on the high P_c technology with a revised schedule on propellant inlet temperatures. Activities on the low pressure phase were terminated by a stop work order, which eliminated the requirements for a portion of the injector testing and all of the low P_c cooled chamber fabrication, durability and pulse testing. The program's resources originally planned for these activities have been reallocated to expand design and test efforts related to the lower temperature gaseous propellants. The high P_c technology effort is now in, the full 40:1 nozzle/thrust chamber, assembly, test phase.

Mr. L. Schoenman, project manager for the high pressure phase, reports to Dr. R. J. LaBotz, who is program manager of all ALRC APS thruster programs. The NASA Lewis Research Center program manager is Mr. J Gregory.

II. PROGRESS BY TASK

A. ACTIVITIES FOR AMBIENT TEMPERATURE PROPELLANTS

1. Task I - Injector Analysis and Design

No activity.

2. Task II - Injector Fabrication

The fuel inlet line and feed manifold of S/N-4 premix triplet injector were modified to mate with the film cooled chamber.

3. Task III - Cooled Chamber Analysis and Design

No activity.

4. Task IV - Chamber Fabrication

a. Hardware Status

The status of the four cooled chambers at the close of the report period are as follows:

Film Cooled Chamber

S/N-1 Fabrication and instrumentation complete. Thrust chamber is on the J-3 test stand.

S/N-2 Fabrication complete; leak and cold flow checkouts satisfactory. Strain gage instrumentation complete; thermal instrumentation in progress.

I. PROGRAM OBJECTIVES

The primary objective of this contract is to generate a comprehensive technology base for high performance gaseous hydrogen-gaseous oxygen rocket engines suitable for the Space Shuttle Auxiliary Propulsion System (APS). Durability requirements include injector and thrust chamber designs capable of 50 hours of firing life over a 10-year period with up to 10^6 pulses and single firings up to 1000 sec. These technical objectives are being accomplished and reported upon in a 28-task program summarized below. The first 10 tasks relate to high pressure APS engines, parallel tasks XI through XX relate to low pressure APS engines, and task XXI is a common reporting task. The additional tasks are for the expanded High P_c Low Temperature Program.

Task Titles	High P_c Task		Low P_c Task
	Amb. Prop.	Low Temp Prop.	
Injector analysis and design	I*	XXII	XI*
Injector fabrication	II*	XXIII	XII*
Thrust chamber analysis and design	III*	XXIV	XIII*
Thrust chamber fabrication	IV	XXV	XIV*
Ignition system analysis and design	V*	--	XV*
Ignition system fabrication and checkout	VI*	--	XVI*
Propellant valves preparation	VII*	--	XVII*
Injector tests	VIII*	XXVI	XVIII*
Thrust chamber cooling tests	IX	XXVII	XIX*
Pulsing tests	X	XXVIII	XX*

Common Task

Reporting requirements XXI

*Completed tasks for revised program.

II,A,4,a, Hardware Status (cont.)

Regeneratively Cooled Chamber

S/N-1 Fabrication complete; leak check and cold flow complete; instrumentation in progress.

S/N-2 Fabrication complete with exception of electroformed nickel case. Part will be shipped to Electroforms, Inc., for electroforming and returned for final stress relieving, machining and instrumentation in about 10 days.

Fabrication Task Summary

The 40:1 cooled thrust chambers designed and fabricated under this task employed proven state-of-the-art fabrication methods. Fabrication of these chambers has proceeded, to date, without encountering major fabrication difficulties. Minor problems periodically encountered were resolved and all components completed are of a quality which is acceptable for this technology program.

The spinning of stainless steel skirts to the Rao nozzle contour was proven to be a simple low cost operation which is most applicable to quantity production. The same is true of the use of photoetched nozzles for the supersonic film cooling injection ring. The spinning operations on the Haynes 188 throat sections from conical rolled and welded preforms proved somewhat more difficult and time consuming because of the need for frequent heat treatment and descaling operations. Slight modifications to the conical preforms for future parts would greatly reduce the number of heat treatment cycles and make the component suitable for low cost quantity production.

II,A,4,a, Hardware Status (cont.)

Initial difficulties in cutting deep narrow slots in the regeneratively cooled copper chamber were a result of using non-optimum tooling and cutting rates. Slotting operations proceeded smoothly once proper cutters were obtained and feed rates established. All designs employ constant width cooling channels and are free of splits or bifurcations. Components containing cooling channels, therefore, also lend themselves to low cost quantity production.

Two approaches to coolant channel closeout employed were (1) shrink fit the copper liner containing the coolant channels into a thin wall .060 in. steel tubular jacket for the film cooled design, and (2) braze rectangular wires into a stepped coolant slot for the regeneratively cooled chamber design.

In the latter approach, the initial channel is cut with a .060 in. wide cutter and .060 in. constant depth. A second variable depth .050 in. wide contour cut formed the coolant channels of variable cross-sectional flow area. Channel closeout was accomplished by brazing precontoured .060 in. square copper wires into the slots. The .005 in. ledge formed by the stepped machining provides a positive channel depth control.

Braze assembly of components was conducted on a one-chamber-at-a-time schedule. In some instances it was necessary to repeat a braze run to obtain proper flow of braze material, and to install gas side thermocouples or flanges. The ability to recycle components at or after the final assembly stage is a desirable feature.

The pressure vessel structure in the regeneratively cooled design is provided by electroforming a thin nickel jacket over the chamber, following the wire braze. The electroformed nickel is isolated from the hydrogen by the wire closeout and, therefore, not subject to the embrittlement phenomena associated with the material.

II,A,4,a, Hardware Status (cont.)

The shrink fit and braze approach to closure employed on the film cooled design has proven to be simpler and less time consuming than the square wire braze and has the following advantages: (a) the expansion coefficient of copper and stainless steel are nearly identical as compared to 2×10^{-6} in/in^{o}F differential between copper and nickel, (b) the steel/copper assembly can be rebrazed to permit installation of gas side thermocouples. Limitations inherent in the electroforming closure are the inability to braze in gas side thermocouples following electroforming due to potential blistering of the electroformed surface. When thermocouples are brazed prior to electroforming, it becomes impractical to finish machine the rough exterior surface. Additional undesirable tendencies noted on the first chamber assembly includes non-uniform material deposition in both the circumferential as well as axial directions and some minor chamber warpage. A modification to the electroforming procedure is being evaluated for the second chamber assembly to determine if some of these shortcomings can be overcome.

Chamber Acceptance Tests

In addition to normal leak and pressure tests, each finished chamber is cold flowed with GN_2 to determine: (a) chamber flow coefficient; and (b) flow uniformity within the coolant channels and to detect possible plugged channels. Figure 1 shows the coolant channel flow distribution in S/N-2 film cooled chamber using a single inlet to feed a constant area manifold. Flow distribution falls within $\pm$ 10% of the nominal values with the exception of several channels located on either side of the inlet line. The low flow condition on either side of the inlet port has been determined to be a result of the manifold aerodynamics rather than obstructed channels because it is reproducible in both S/N-1 and S/N-2 chambers. The locally low flow conditions, although acceptable for the technology program, will tend to result in undesirable thermal gradients around the chamber periphery and thus be detrimental to chamber life. When the chamber was flowed with double inlet ports, 180 degrees apart,

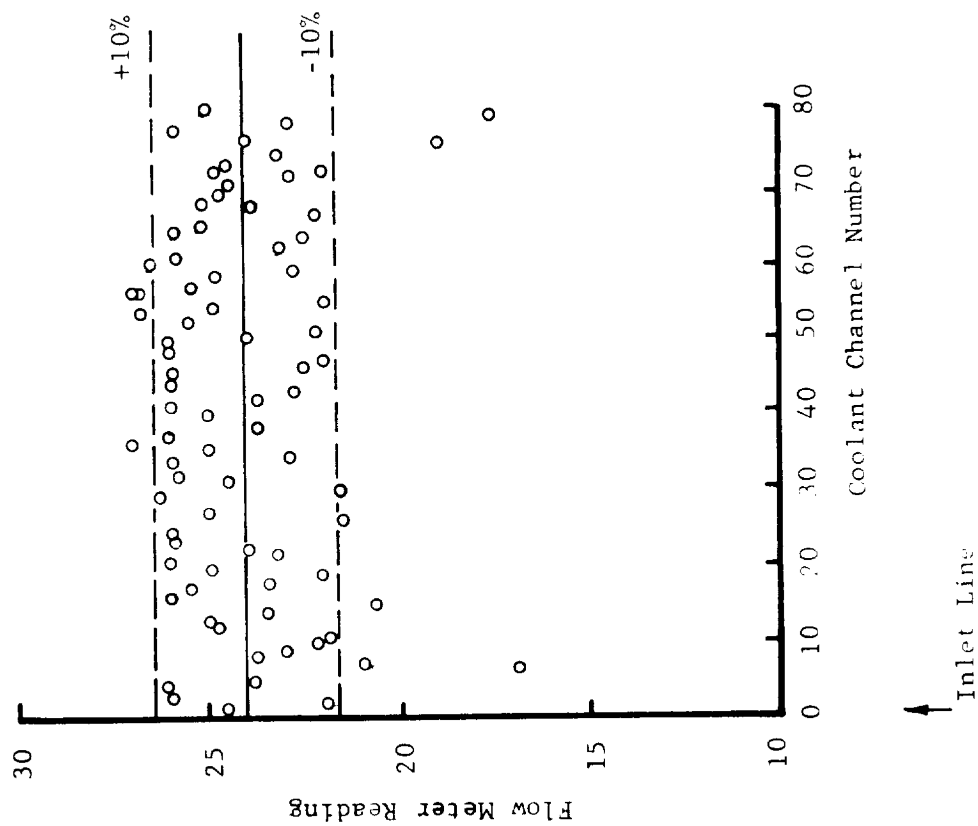


Figure 1 -- S/N-2 Film Cooled Chamber Coolant Jacket Flow Distribution

II,A,4,a, Hardware Status (cont.)

flow distribution was improved. A somewhat more elaborate manifold or baffling will be recommended for future single inlet designs to improve this condition.

Similar cold flow test data for the S/N-1 60-channel regeneratively cooled chamber are shown in Figure 2. The coolant inlet manifold in this design is fed at two locations spaced 180 degrees. All channels were found to be open and flowing uniformly within a range of ± 10%. This flow condition is considered satisfactory.

5. Task V - Igniter Design and Analysis

No activity.

6. Task VI - Igniter Checkout Tests

No activity.

7. Task VII - Valve Preparation

No activity.

8. Task VIII - Injector Checkout Tests

No new activities were conducted on this task, however some of the test results are still being reviewed. Section III,A,3, in Report 13454-Q-3, presented the thermal characteristics of heat sink copper chambers with and without the use of film cooling. Two significant factors were noted. One was the experimental verification of the thermal model which predicted higher heat transfer coefficients when fuel film cooling is employed. The other was an observation that the heat flux vs. wall temperature curves contained a higher-than-predicted value at low wall temperatures (early time in the run). Further analysis of the engine start transient dynamics in the Bay 7

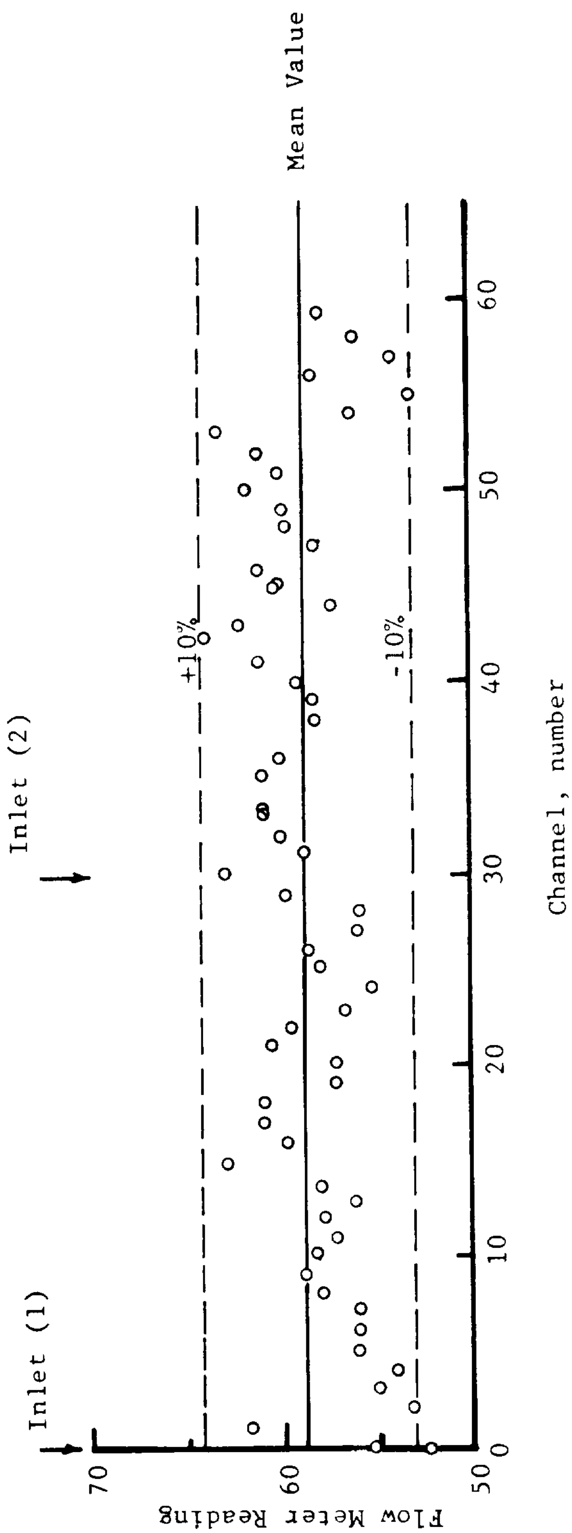


Figure 2 -- S/N-1 Regeneratively Cooled Chamber Coolant Channel Flow Distribution

II,A,8, Task VIII - Injector Checkout Tests (cont.)

Test Facility which employed critical flow nozzles fed through a pressure regulator is shown in Figure 3. This plot shows the engine and facility flow parameters vs. time in the upper half and throat heat flux vs. time in the lower half. The prefire pressures at which the regulators are set are higher than steady-state to accommodate regulator-to-venturi line losses. This results in a correspondingly higher propellant weight flow during the first few tenths of a second after the thrust chamber valves are opened. These initially higher weight flows in turn result in the momentarily higher heat flux. When the data (solid points) in Figure 3 adjusted to the steady-state flow rate, a lower heat flux (half shaded points) results. The adjusted heat flux is 15 to 20% lower in the early times and would reduce the heat transfer coefficients calculated from short tests in the copper chamber by a like amount. This correction makes the short duration copper chamber data of Figure III-7, Report 14354-Q-3, agree reasonably well with both the longer tests on the thin wall steel chamber and the heat transfer model predictions.

The above discussion does not apply to the performance data since performance is based on a summary period which starts at 1.0 sec.

9. Task IX - Cooled Chamber Testing

a. Test Facility

Testing of 40:1 nozzle thrust chamber assemblies in the J-3 altitude facilities was initiated during this report period. This facility provides the capability of holding ambient pressures of less than 0.5 psia for up to several thousand seconds and sustained fire durations of 500 sec. The facility also contains an on-line computer (analog) which both controls and monitors critical engine operating parameters. The control of propellant flow rates (and thus thrust and mixture ratio) is accomplished via three flow control vales, i.e., fuel, oxidizer and fuel film cooling. The

Test Parameter Nomenclature

F	Thrust
PFJ	Injector Fuel Manifold Pressure
POJ	Injector Oxidizer Manifold Pressure
PC	Chamber Pressure
PFV	Venturi Inlet Pressure, Fuel
POV	Venturi Inlet Pressure, Oxidizer
PFVC	Venturi Inlet Pressure, Film Coolant
MR	Mixture Ratio

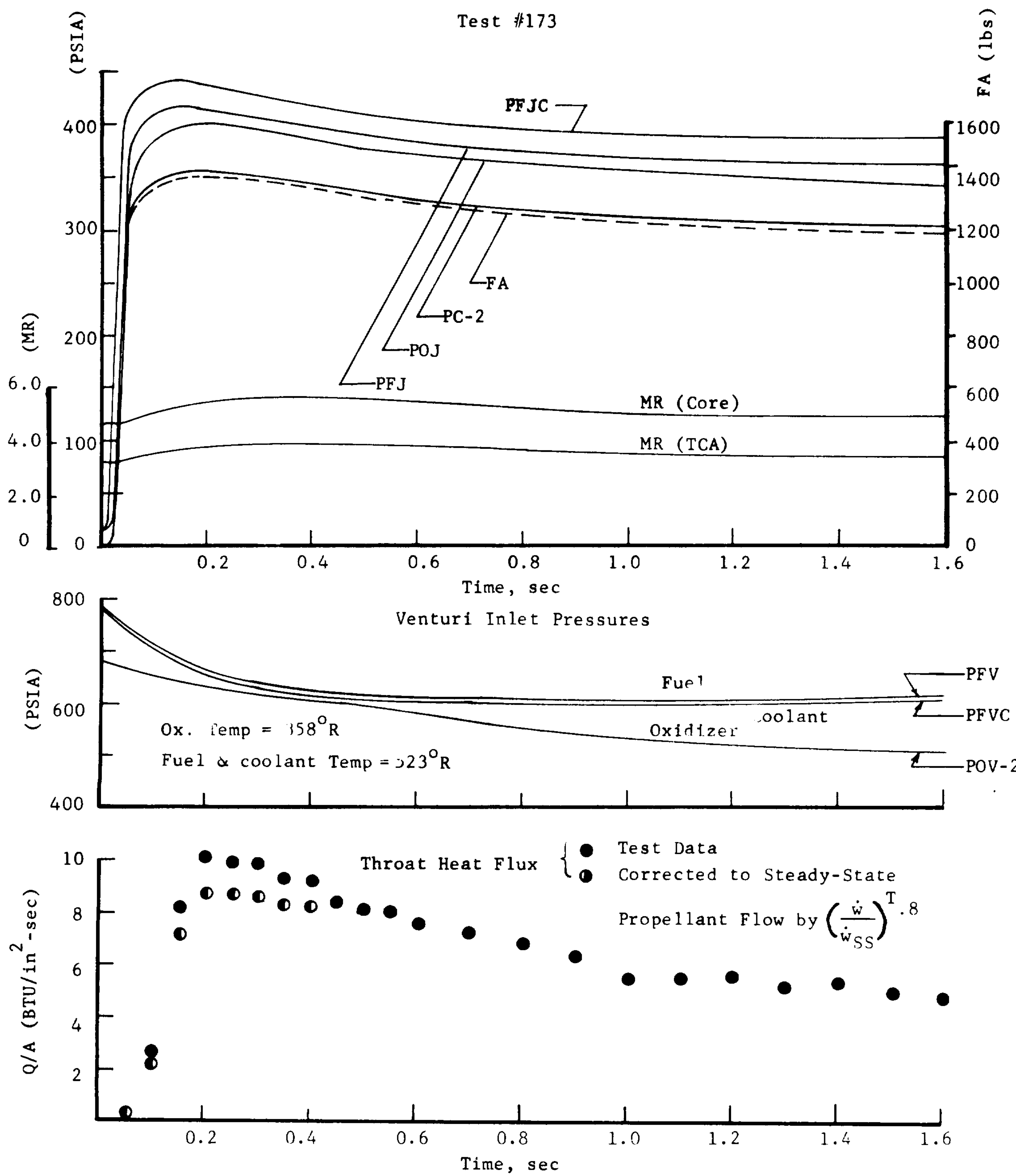


Figure 3 -- Physics Lab Bay 7 Thrust Chamber Start Transients Using Critical Flow Control Venturies

II,A,9,a, Test Facility (cont.)

computer holds the preselected respective flow rates by positioning each flow control valve to maintain a specified pressure at the inlet to critical flow nozzles using both nozzle inlet pressure and temperature measurements in the feedback loop. The computer is preprogrammed to provide TCA mixture ratios of 3, 4 and 5, with either 20, 25, or 30% film cooling at each MR, and to balance for either 100, 300 or 500 psia chamber pressures. Other film cooling flow rates can be programmed in by simply setting a dial. Mixture ratios and cooling flow rates can be changed by signal from the control console while the engine is firing.

The computer further monitors up to six engine parameters (temperature or pressure) and provides a means of automatically shutting down if values are not within specified safe operating ranges. Parameters normally monitored are injector face, nozzle throat and skirt temperatures, and chamber pressure.

The tubular heat exchangers which provide either hot or cold conditioned propellants for unlimited test durations were installed during this period, but have not been checked out because of the heavy testing schedule on this program.

b. Summary of Testing (Series 1680-D04-0A)

Testing in this task is summarized in Table I. In order to check out the dynamics of the computer controlled system during mixture ratio changes and obtain a performance base point for comparison of J-3 altitude vs. physics lab Bay 7 (Task VIII) data, initial J-3 tests were conducted with residual Task VIII injectors and 3:1 area ratio film cooled steel chambers.

Table I -- Summary of Task IX Tests

Test No.	Date	Inj. S/N	Chamber	Data Summary Period, sec	L'/L*	P_c PFJI	TCA MR	% FFC	TCA W_t lb/sec	F_{Meas} lb	P_{Alt}	MR_J	Prop. Temp.	F_{Vac} (Unc.)	I_{sv} Unc./Corr.	C*	% C* Unc. P_c-1A
1680-D03-0A																	
-001	System and Igniter Checkout Tests																
-002	System and Igniter Checkout Tests																
-003	System and Igniter Checkout Tests																
-004	System and Igniter Checkout Tests																
-005	4/30/71	2 I	3:1 FC	.4-.6	5.5/15	256	3.99	32.7	3.196	977.6	11.28	6.08	Amb.	1075.6	336.5	7468	
-006	4/30/71	2 I	3:1 FC	.4-.96	5.5/15	269.4	3.000	32.05	3.237	1025.6	10.97	4.51		1120.9	346.3	7759	
-007	4/30/71	2 I	3:1 FC	.4-.91	5.5/15	268.0	3.022	31.4	3.23	1033.8	10.94	4.49		1128.8	349.5	7735	
-008	4/30/71	2 I	3:1 FC	15.0-20.0	5.5/15	<250>	3.00	30.2	3.29	980.8	10.64	4.39		1073.2	326.2	<7084>	
-009	4/30/71	2 I	3:1 FC	5-10	5.5/15	<258>	2.93	29.7	3.29	1047.7	10.53	4.24		1139.2	346.2	<7169>	
-010	5/12/71				7.5/20	Sea Level - Igniter Only											
-011	5/12/71					Altitude - Igniter Only											
-012	5/12/71					P_{Alt} 1A Bad No Perf. Dam.											
-013	5/12/71	5 I	40:1 FC/Cu	6.0-9.6		284.9	3.87	31.8	3.52	1354.9	1.037	5.87	Amb.	1473.4	418.6	7438	90.7
-014	5/14/71	5 I	FC/Cu	30-35		290.2	3.96	30.6	3.52	1289.5	1.075	5.90		<1412.4>	401.5	7583	92.5
-015	5/14/71	5 I	FC/Cu	20-50		290.0	3.93	30.6	3.50	1369.4	1.116	5.86		1497.0	429.0	7583	92.5
				60-90		295.0	3.88	24.9	3.51	1389.3	1.161	5.33		1389.4	434.8	7727	94.4
				100-130		298.4	3.86	19.4	3.51	1400.6	1.190	4.92		1536.7	438.3	7804	95.5
				143-165		303.1	2.93	29.5	3.52	1385.5	1.237	4.26		1526.8	435/439	7921	94.8
				173-193		306.1	2.92	25.3	3.52	1384.1	1.239	4.01		1525.7	434/444	8004	95.9
				200-225		307.7	2.95	20.3	3.51	1381.2	1.232	3.79		1522.0	435/448	8066	96.6
				245-270		278.3	4.84	30.0	3.51	1262.8	1.175	7.207		1397.1	401/414	7278	91.7
-016	5/21/71	4 Trip	FC/Cu	Computer shut down due to amplifier malfunction													
-017	5/21/71	4 Trip	FC/Cu	4.0-5.0		291.0	2.95	28.6	3.36	1390.3	.615	4.24	Amb.	1460.6	434.1	7948	94.7
				4.5-5.0		291.4	2.95	28.6	3.37	1389.2	.695	4.24		1468.6	436.0	7951	94.8
-018				4.0-4.5		296.5	2.94	25.4	3.41	1404.7	.728	4.04		1487.6	436.6	7995	95.2
				4.0-5.5		297.5	2.95	25.3	3.41	1387.0	.901	4.05		1489.9	436.5	8007	95.4
-019				.5-1.5		276.0	4.00	23.7	3.33	1390.9	.190	5.43		1412.6	424.8	7626	93.0
				3-8		284.4	3.98	25.1	3.43	1420.6	.346	5.49		1460.2	425.8	7622	92.95
				9.2-11.5		289.2	3.94	19.1	3.43	1412.8	.560	5.02		1476.8	430.5	7746	94.5
-020				.6-1.0		279.2	4.02	24.5	3.37	1404.1	.180	5.52		1424.6	423.3	7624	93.0
				4.0-6.0		285.4	4.00	24.9	3.44	1426.7	.331	5.51		1464.6	425.4	7618	92.9
				10.0-14.0		289.4	3.95	19.1	3.44	1399.0	.655	5.03		1473.8	428.3	7733	94.3
				17.0-22.0		279.5	4.03	30.5	3.42	1304.4	.970	6.01		1415.1	413.7	7507	91.5
				30-50.0		268.4	4.86	23.6	3.43	1345.1	.566	7.35		1409.7	410.5	7182	90.3
-021				5-50		93.9	4.44	21.4	1.15	464.3	.140	5.86		480.3	318.1	7514	92.8
				55-105		93.1	4.39	26.6	1.15	398.0	.140	6.22		474.4	411.8	7429	92.0

< Data Invalid> Instrumentation calibration shift during test

II,A,9,b, Summary of Testing (Series 1680-D04-0A) (cont.)

Tests 001 through 004 were valve, igniter sequence, and cold flow tests.

Tests 005 through 009 were system debugging and calibration tests with S/N-2 I premix injector, a 3:1 area ratio film cooled chamber and a 25-lb thrust spark igniter. Tests were conducted at partial altitude conditions to prevent accumulation of combustible gases in the test cell.

Tests 005, 006 and 007 were terminated between 0.6 and 1.0 sec by computer because of programming errors in the temperature shutdown criteria. Data points were obtained at TCA mixture ratios of 4, 3, 3, with nominal 30% film cooling.

Tests 008 and 009 with the same hardware were of 23 and 28 seconds duration in which both film cooling and mixture ratio were varied while the engine was firing. Test 008 and test 009 proceeded as follows.

Test	Period (sec)	MR	% Cool
008	0 - 6	3.0	33
	7 - 11	3.0	30
	12 - 16	3.0	25.5
	17 - 20	3.0	33
	21 - 23	4.0	37
009	0 - 14	3.0	30
	14 - 28	4.0	35

Accumulation of moisture in the load cell due to operation at partial vacuum resulted in questionable thrust measurements in the latter tests of this series. The facility however appeared to be operational at this point.

II,A,9,b, Summary of Testing (Series 1680-D04-0A) (cont.)

Tests 010 through 015 were conducted with S/N-5A premix I triplet injector, S/N-1 film cooled 40:1 nozzle and the same spark igniter. Test 010 consisted of three igniter-only firings prior to evacuating the cell. Normal ignition was achieved in each case. Test 011 was a repeat series at altitude of 69,000 ft. The igniter was fired three times in series and three normal igniter ignitions were achieved. Test 012 was a 1-sec thrust chamber firing MR = 4.0, 30% film cooling. Real time data playback indicated that all thermal and pressure parameters appear to function as predicted. The same test conditions were immediately repeated without hardware inspection in Run 013 for a 10-sec duration. Postfire inspection following the 10-sec test revealed the hardware to be in excellent condition.

The above test conditions were repeated for a 37-sec run (Test 014) during which steady-state temperatures were achieved throughout the nozzle.

Test 015 was initiated immediately following a brief data review and lasted for 278 seconds. During this continuous fire period the 11 following nominal balance conditions were evaluated.

MR	Data Points	% Film Cooling
4	(a - d)	30, 25, 20, 30
3	(e - h)	30, 25, 20, 30
4	i	30
5	j, k	30, 25

Testing was terminated due to a significant rise in cell pressure caused by depleated levels in the facility accumulator/ejector system. Steady-state thermal conditions were achieved at each condition except the last. Postfire hardware inspection revealed major local damage to the injector face under the oxidizer inlet, no damage to the chamber, igniter, facility, or instrumentation. Data analysis revealed failure was initiated 18.5 sec prior to shutdown

II,A,9,b, Summary of Testing (Series 1680-D04-0A) (cont.)

and was undetected because of only minor changes in the temperature, pressure, and performance parameters being monitored. The cause of the failure is believed to be obstruction of one or more oxidizer orifices with foreign material. Figure 4 shows a photograph of the film cooled thrust chamber assembly mounted on the test stand within the J-3 altitude test cell prior to testing. Figure 5 shows the same nozzle after test 015 at which time four restarts and 326 seconds of duration had been accumulated. Figures 6 through 9 provide a graphical record of the propellant flow rates, and some of the pressure and temperature parameters monitored during test 015. Instrumentation location and nomenclature is identified in the third quarterly report. Changes in flows, and thus chamber wall temperatures throughout the run are initiated by the preprogrammed computer control system.

Runs 016 through 021 employed the same hardware except the S/N-5A injector was replaced by S/N-4 premix triplet which was employed earlier in a 2500 pulse test series in Bay 7 of the Physics Lab. Run 016, a repeat test at MR = 3.0, 20% film cooling, was computer terminated due to an amplifier malfunction feeding throat temperature data to the computer.

Runs 017, 018, and 019 were short (5 sec) tests to obtain repeat performance with S/N-4 injector at the following conditions.

Run	MR	% Cooling
017	3	30
018	3	25
019	4	25
	4	20

Run 020 was approximately 50-sec duration during which near steady wall temperatures were reached at the following conditions.

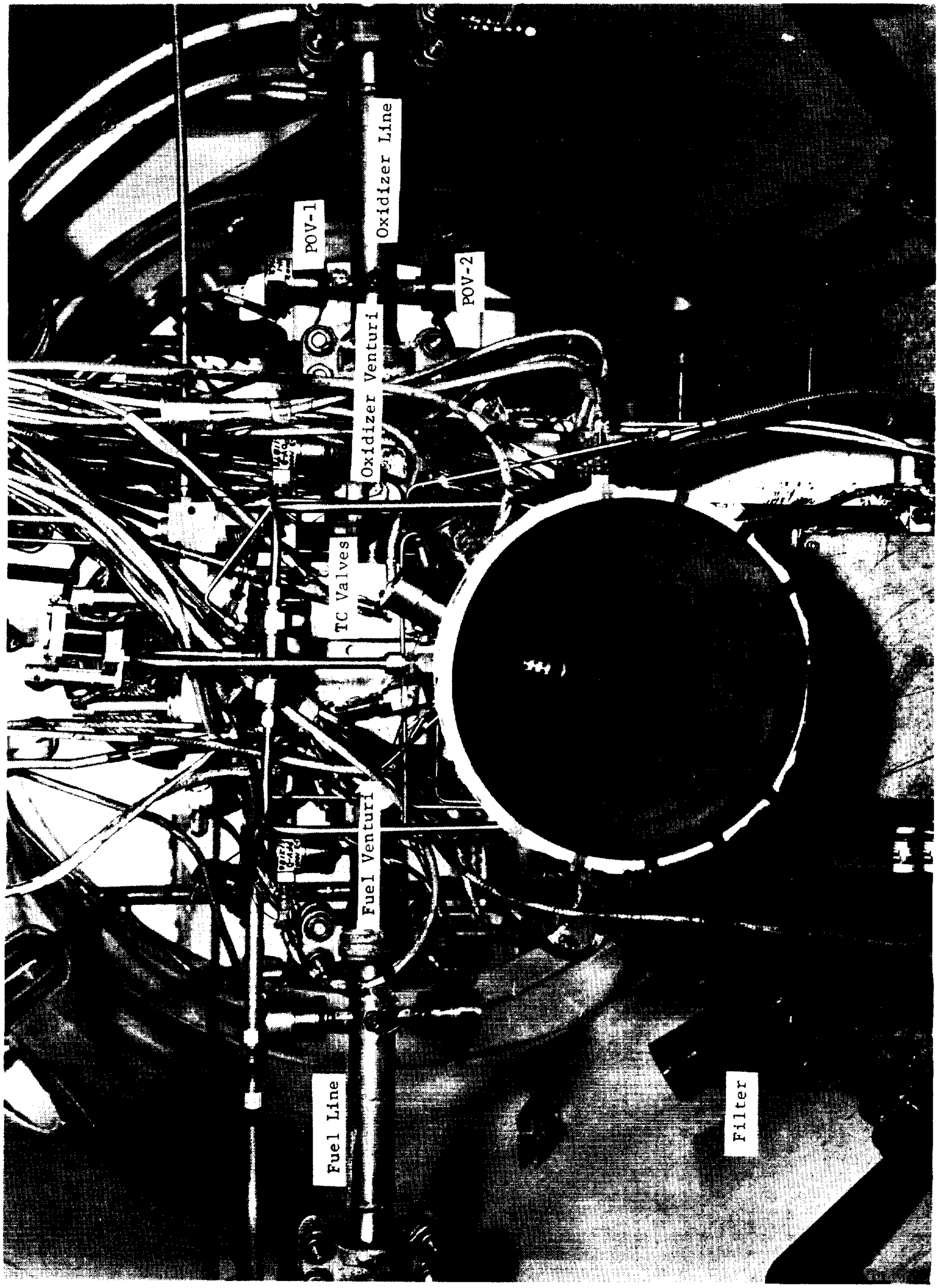


Figure 4 -- Film Cooled Thrust Chamber Assembly on J-3 Altitude Facility (Prefire)

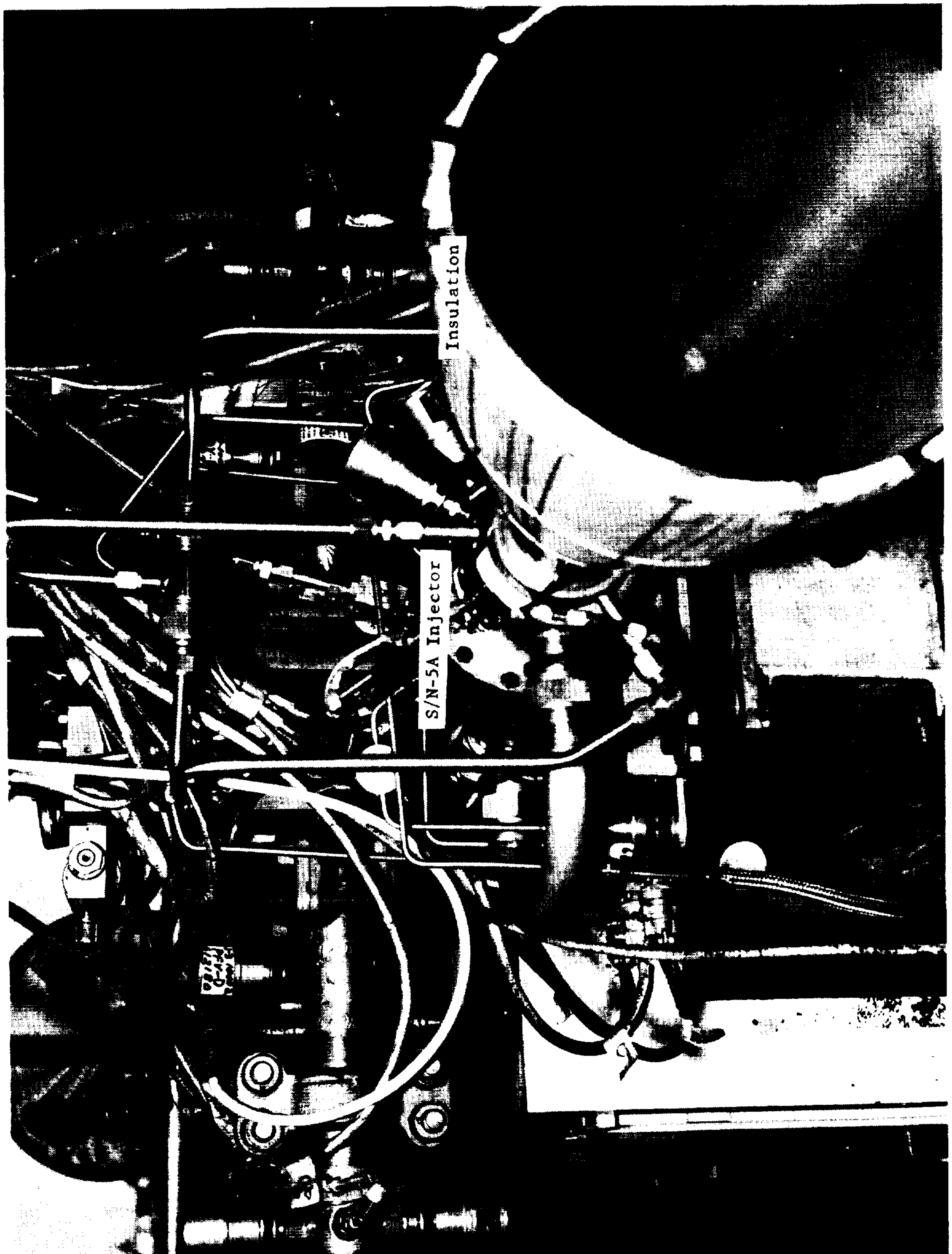


Figure 5 -- Film Cooled TCA in J-3 Altitude Facility
(Postfire)

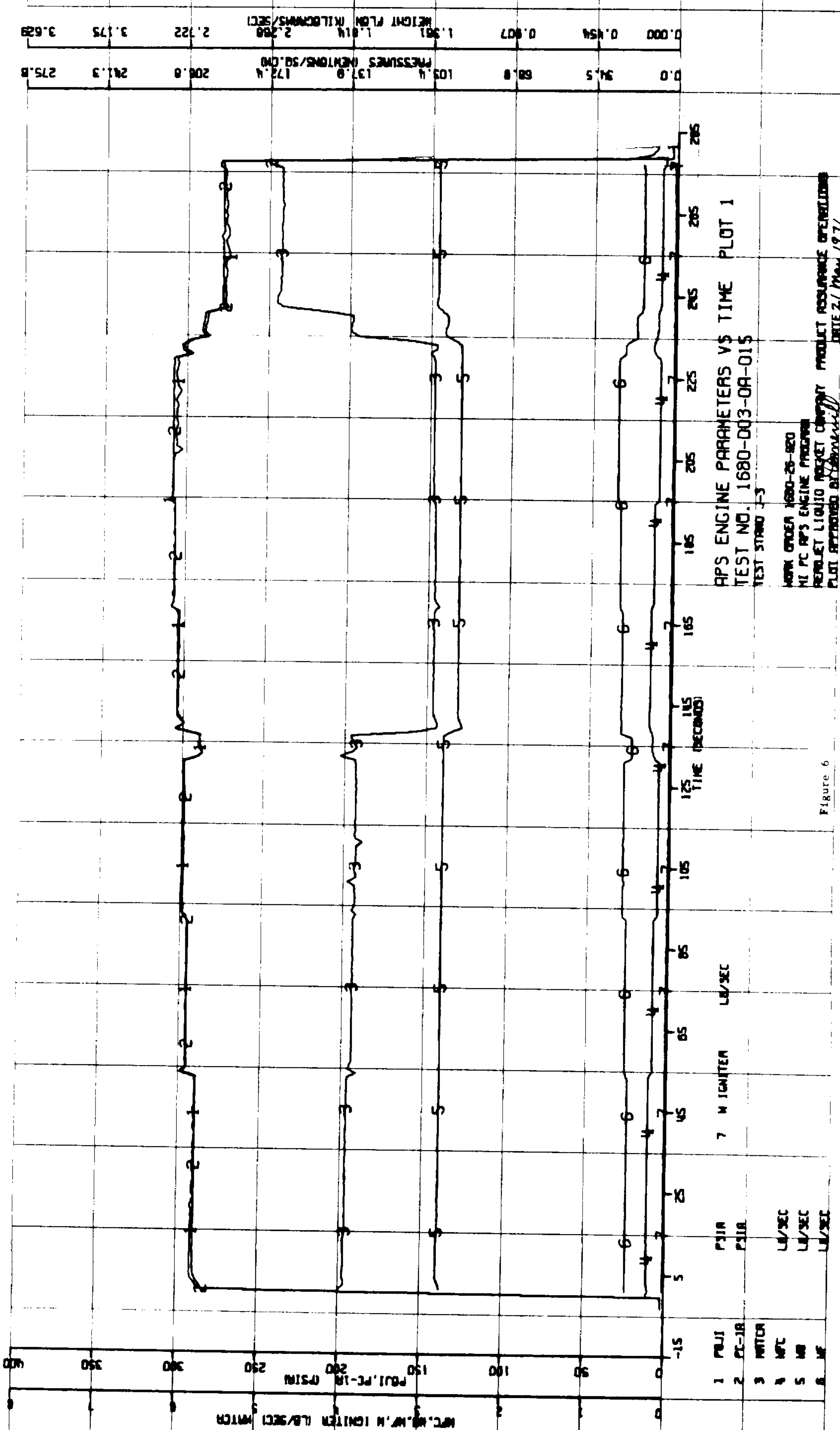
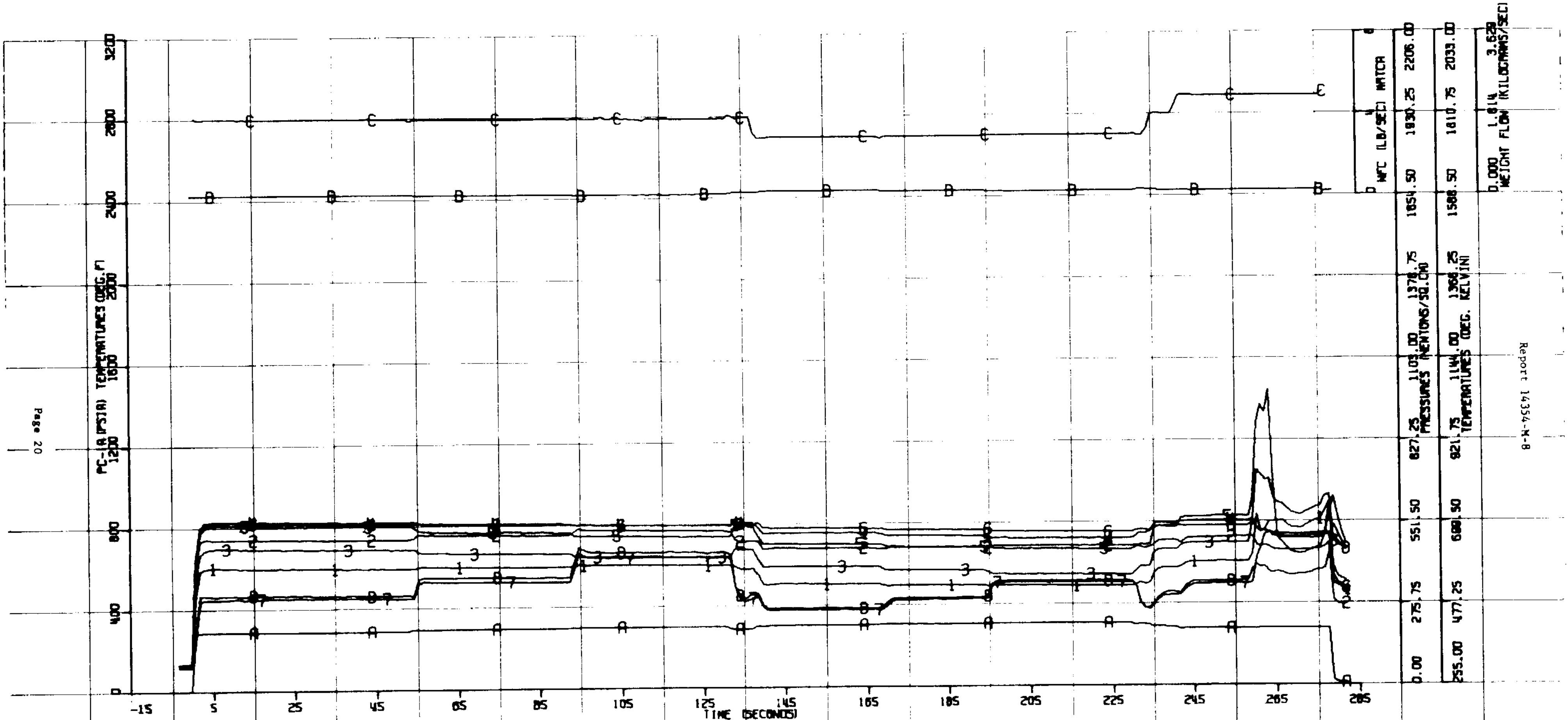

APS ENGINE PARAMETERS VS TIME PLOT 1
TEST NO. 1680-D03-OA-015
TEST STAND J-3
WORK ORDER 1680-26-820
HI PC APS ENGINE PROGRAM
AEROJET LIQUID ROCKET COMPANY
PLOT APPROVED BY
PRODUCT ASSURANCE OPERATIONS
DATE 21 May 1971
WEIGHT FLOW (KILOGRAMS/SEC)
PRESSURES (NEWTONS/SQ.CM)
TIME (SECONDS)
PDJI,PC-1R (PSIA)
WFC,WB,WF,W IGNITER (LB/SEC) WATER
1 PDJI PSIA
2 PC-1R PSIA
3 WATER
4 WFC LB/SEC
5 WB LB/SEC
6 WF LB/SEC
7 W IGNITER LB/SEC

Figure 6



A	PC-1A	PSIA		4	TC10-L	DEG.F
B	WFC	LB/SEC		5	TC11-C	DEG.F
C	MATCA			6	TC11-L	DEG.F
1	TC9-C	DEG.F		7	TL8-A	DEG.F
2	TC9-L	DEG.F		8	TL8-D	DEG.F
3	TC10-C	DEG.F				

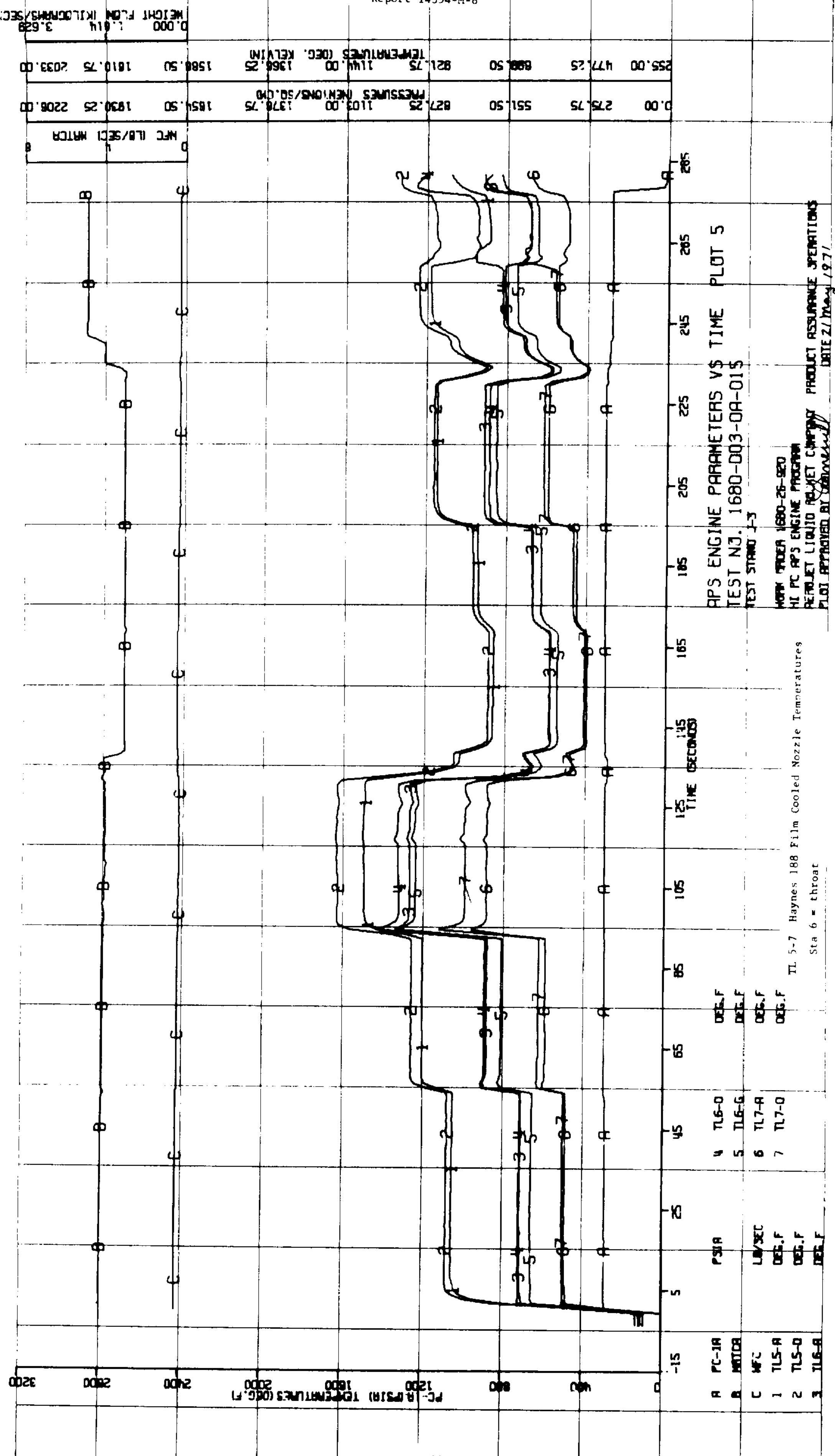
TC 9-11 Gas-Side Wall Temp of Convectively Cooled Copper Combustion Chamber

TC 8 External Temperature at Nozzle Coolant Injection Station

APS ENGINE PARAMETERS VS TIME PLOT 3
TEST NO. 1680-003-0A-015
TEST STAND J-3

WORK ORDER 1680-26-920
HI PC APS ENGINE PROGRAM
AEROJET LIQUID ROCKET COMPANY PRODUCT ASSURANCE OPERATIONS
PLOT APPROVED BY [signature] DATE 21 May 1971

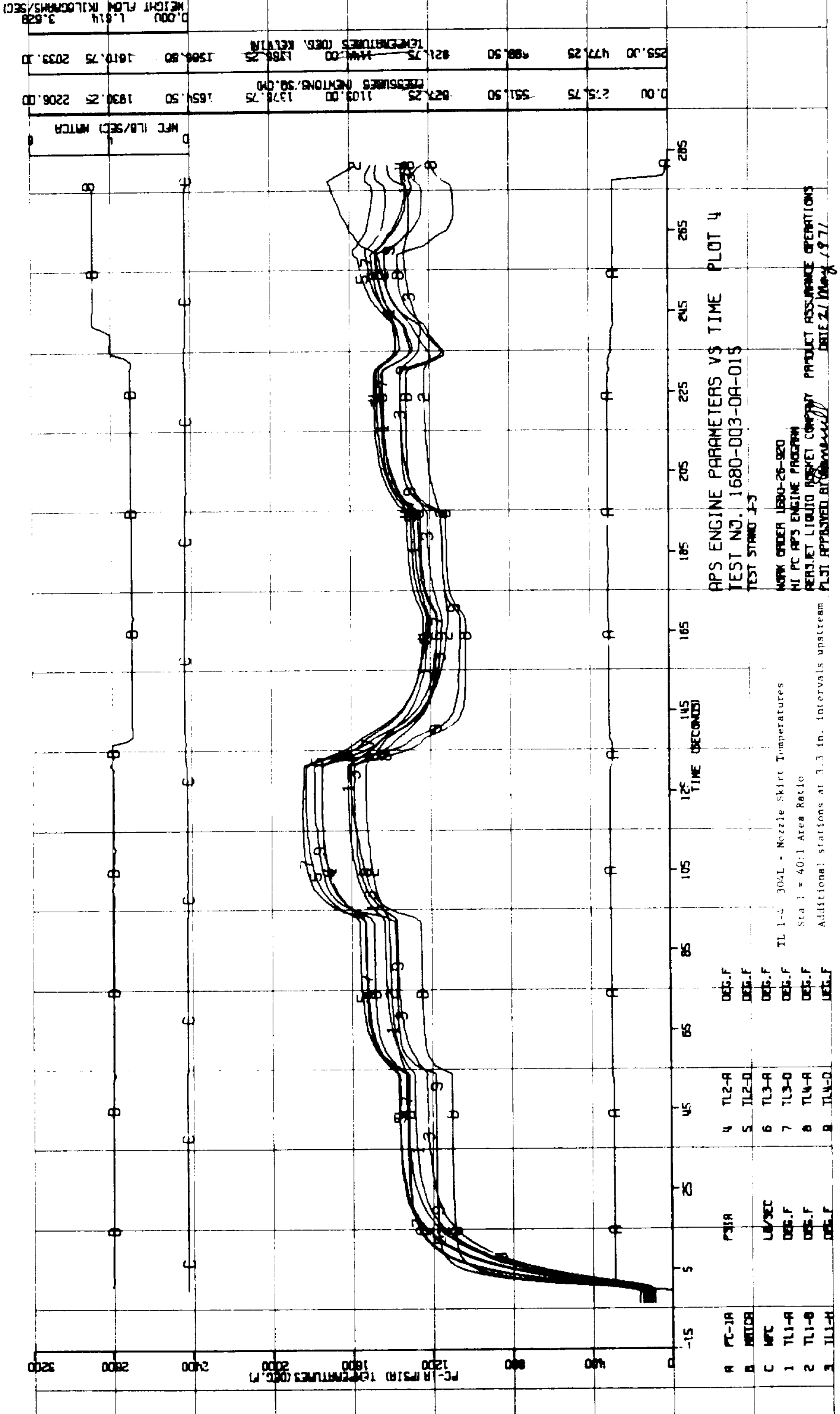
Figure 7



TL 5-7 Haynes 188 Film Cooled Nozzle Temperatures

Sta 6 = throat

Figure 8


APS ENGINE PARAMETERS VS TIME PLOT 4
TEST NO. 1680-003-0A-015
TEST STAND J-3
WORK ORDER 1680-26-920
HI PC APS ENGINE PROGRAM
REARJET LIQUID ROCKET COMPANY PRODUCT ASSURANCE OPERATIONS
PLOT APPROVED BY
DATE 21 May 1971
TIME (SECONDS)
PC-1A (PSIA) TEMPERATURES (DEG. F)
PRESSURES (NEWTONS/SQ.CM)
TEMPERATURES (DEG. KELVIN)
WEIGHT FLOW (KILOGRAMS/SEC)
WFC (LB/SEC) MRTOA
A PC-1A PSIA
B MRTOA
C WFC LB/SEC
1 TL1-A DEG.F
2 TL1-B DEG.F
3 TL1-H DEG.F
4 TL2-A DEG.F
5 TL2-D DEG.F
6 TL3-A DEG.F
7 TL3-D DEG.F
8 TL4-A DEG.F
9 TL4-D DEG.F
TL 1-4 304L - Nozzle Skirt Temperatures
Sta 1 = 40:1 Area Ratio
Additional stations at 3.3 in. intervals upstream

II,A,9,b, Summary of Testing (Series 1680-D04-0A) (cont.)

MR	% Cooling
4	25, 20, 30
5	30

Limiting wall temperatures were approached at the last test condition.

Run 021 was at reduced chamber pressure (100 psia) for a duration of 109 sec. Steady-state thermal conditions were achieved at mixture ratio of 4.0 with 21 and 26% film cooling.

Test Results

Test conditions, duration and performance are summarized in Table I. The performance results should be considered preliminary because of an accumulation of small discrepancies in thrust measurements. In some tests two performance values are provided. The first is the Vac I_{sp} computed from the uncorrected thrust measurements. The second is calculated from the corrected thrust measurements. The performance data (Vac I_s and uncorrected C*) provided in Table I is presented graphically in Figures 10 and 11, while a summary of the axial temperature profiles at the various test conditions and critical temperatures vs. film cooling flow are presented in Figures 12 and 13.

This initial test series has essentially demonstrated the feasibility of the film cooled chamber design and its ability to operate over a wide range of mixture ratios. Film cooling flow rates as low as 19% at nominal design conditions were attained while still maintaining throat and nozzle temperatures which are compatible with long life. Maximum throat and skirt temperatures at the minimum film cooling flow rates were 1250 and 1850^{o}F, respectively. The capability meeting or exceeding the performance

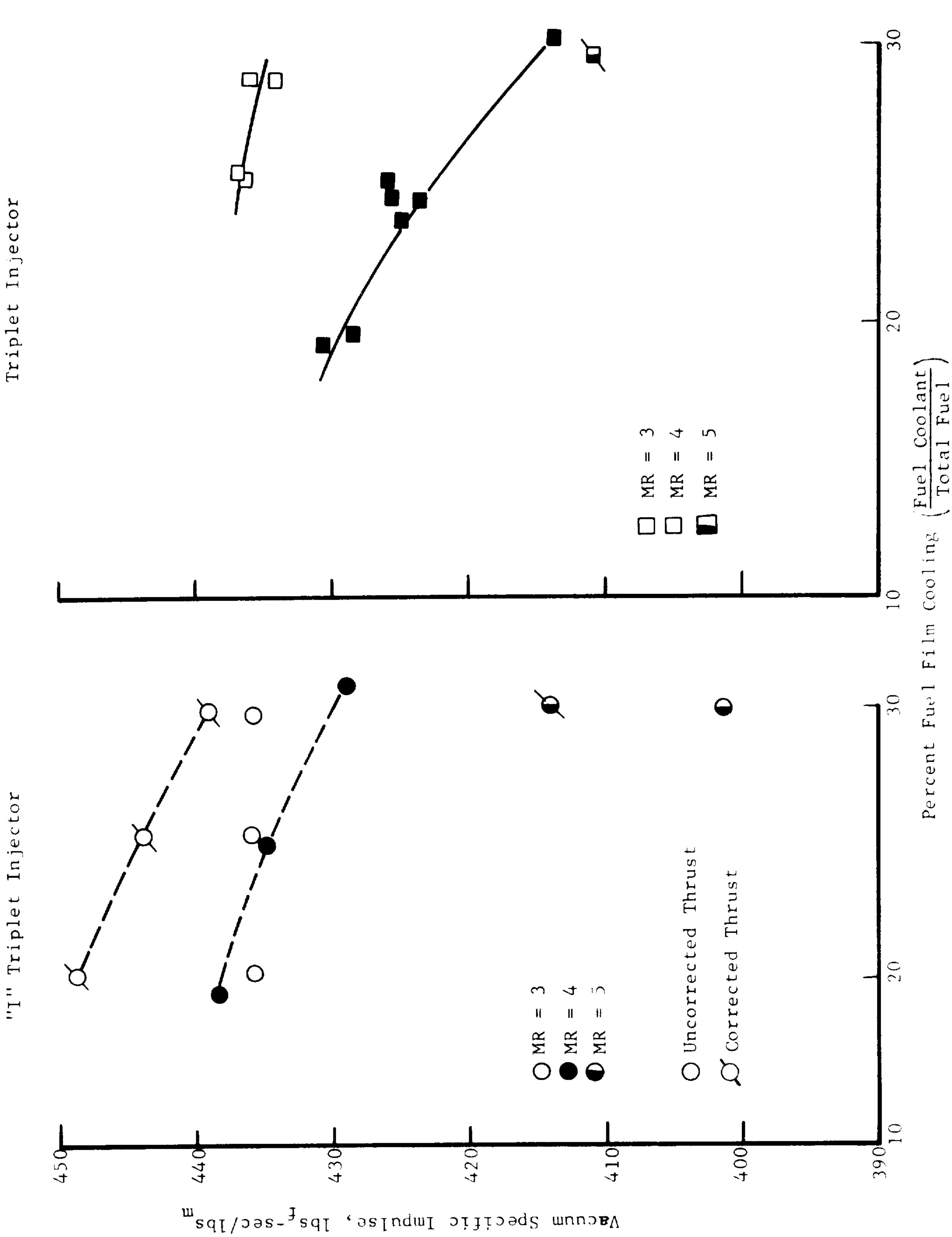


Figure 10 -- High P_c APS Measured Vacuum Performance Film Cooled Chamber
Test Series 1680-D03-0A

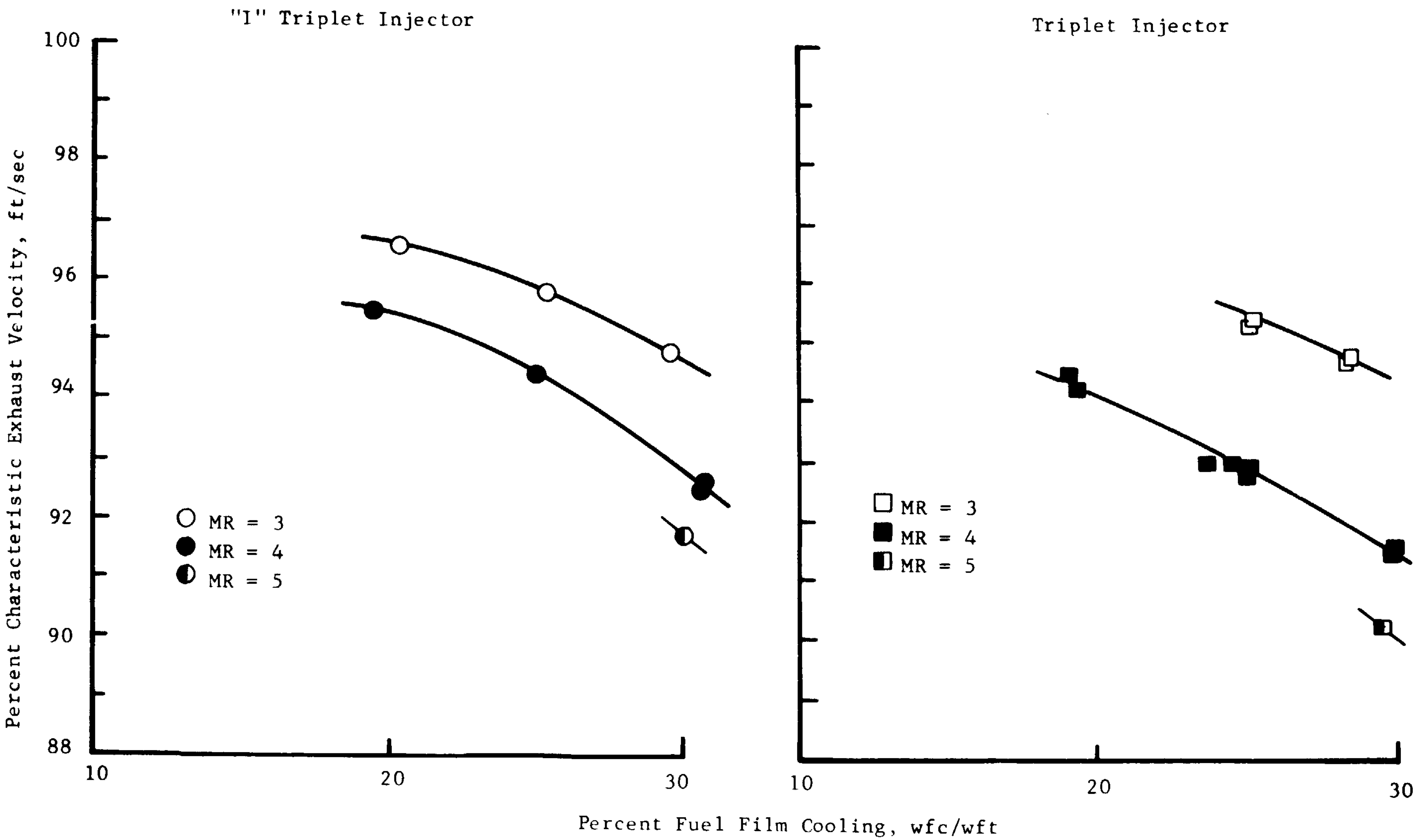


Figure 11 -- High P_c APS Measured Characteristic Exhaust Velocity Efficiency
Test Series 1680-D03-0A
(Wall P_c Tap Film Cooled Chamber)

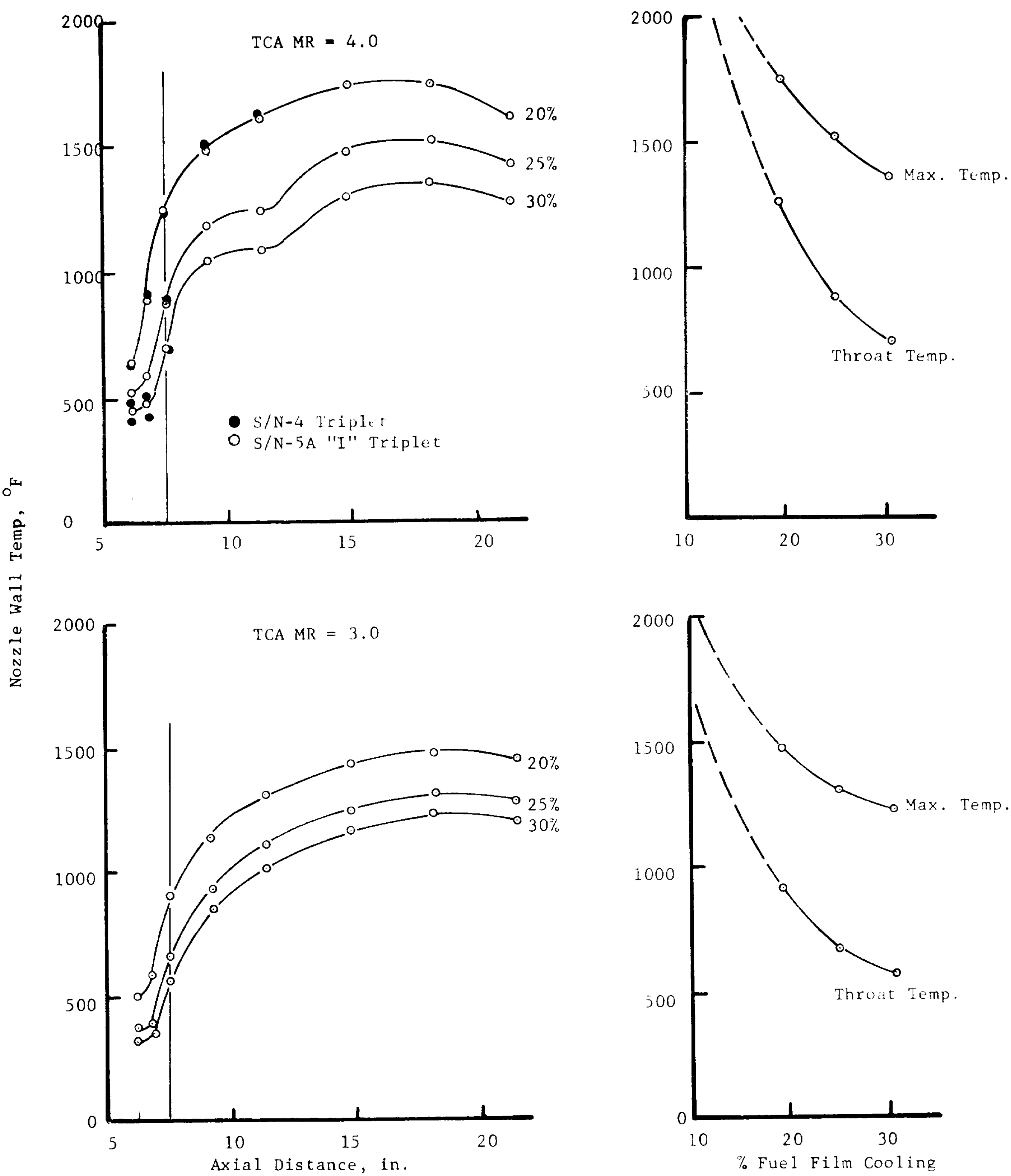


Figure 12 -- Film Cooled Chamber Nozzle Temperature Profiles, 300 psia

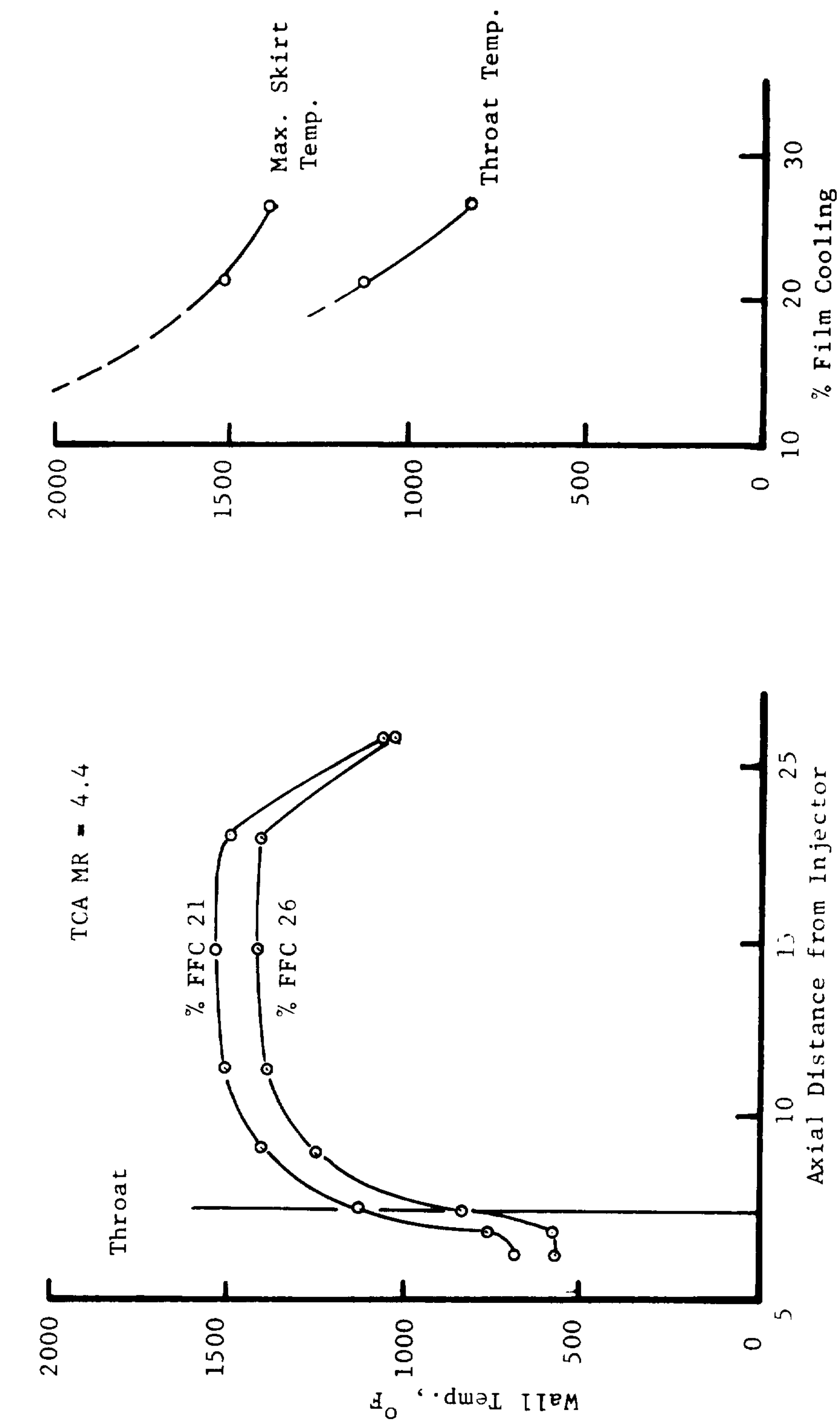


Figure 13 -- Film Cooled Chamber Nozzle Temperature Profiles, 100 psia
Test 021

II,A,9,b, Summary of Testing (Series 1680-D04-0A) (cont.)

goal of 435 sec specific impulse with the premix "I" triplet injector configuration is indicated by the performance data. These data also indicate a 7 to 10 sec performance differential between the "I" triplet and triplet injector pattern. The uncorrected C* data and I_s measurements are consistent in indicating the performance differential. Both injectors produce the same axial temperature profile with the exception of the first three stations downstream of the face at which point the "I" configuration showed about a 100°F higher wall temperature, indicative of more rapid combustion.

Figure 14 provides a comparison of the predicted transient temperatures in the copper lined hydrogen convectively cooled combustion chamber region with gas-side and back-side thermocouple measurements from test 020. Also shown in this figure is a comparison of predicted and measured coolant temperature rise during the first second following ignition.

Maximum steady-state copper temperatures range between 600-650°F compared to a predicted value of 590°F. Steady-state back-side temperatures of 325°F compare to predicted values of 380°F. The steady-state through the wall gradient of 300°F compares with a predicted value of 210°F. The reason for the lower than predicted back-side temperature is being investigated. Maximum thermal gradient of 350°F is achieved in the heating transient starting between 0.3-0.4 seconds into the firing. This confirms the computer prediction of a high early time thermal gradient when the chamber is started cold.

The heat transfer coefficients derived from the transient heating of thin wall film cooled steel nozzle in test 015 is shown in Figure 15. These data are higher than the values obtained by the usual prediction methods noted, but in better agreement with the model which uses local film mixture ratios. The nozzle mass velocity ρV is obtained from the 2-D flow conditions

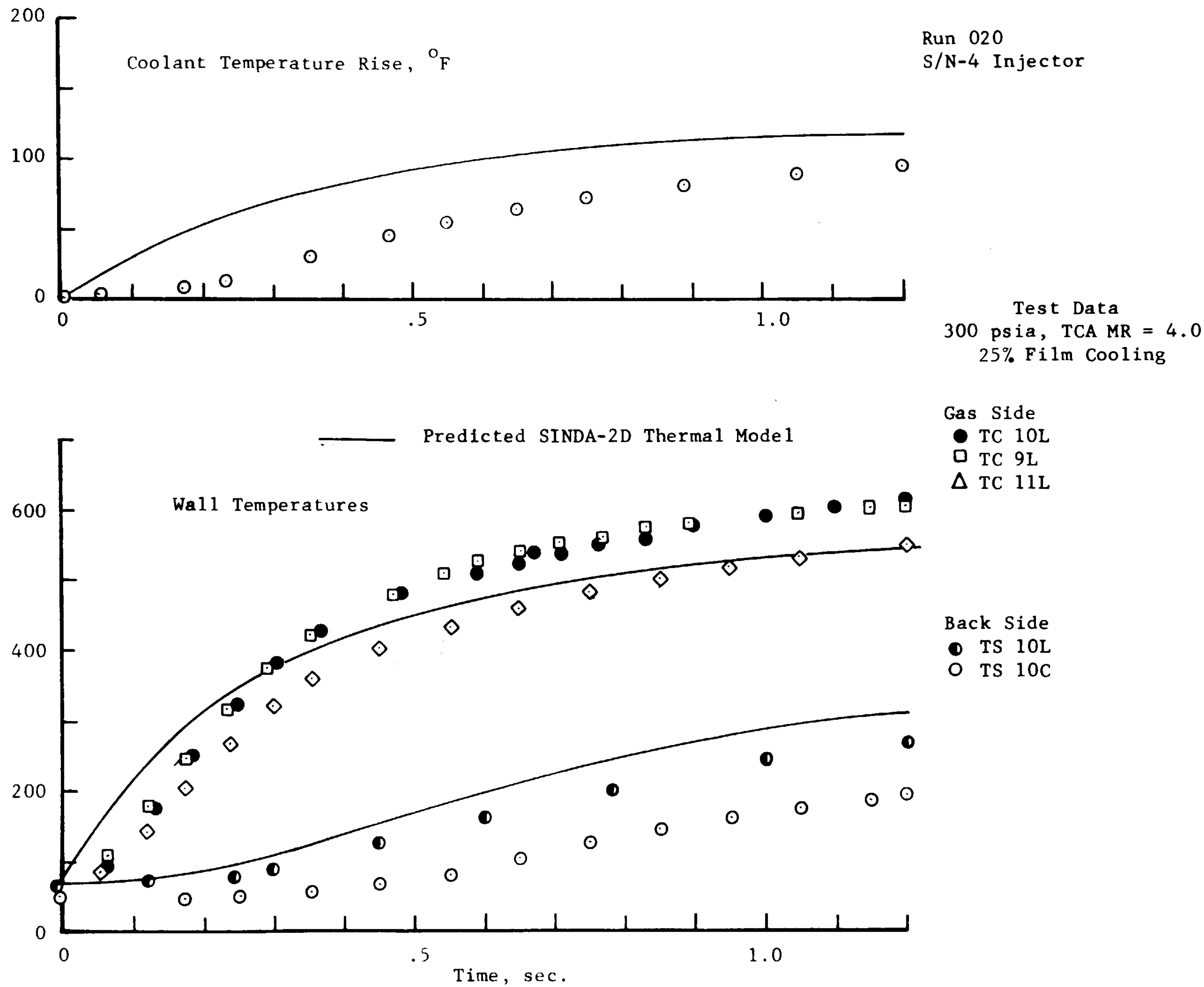


Figure 14 -- Combustion Chamber Temperatures, Film Cooled Chamber, P/N 1160334-1

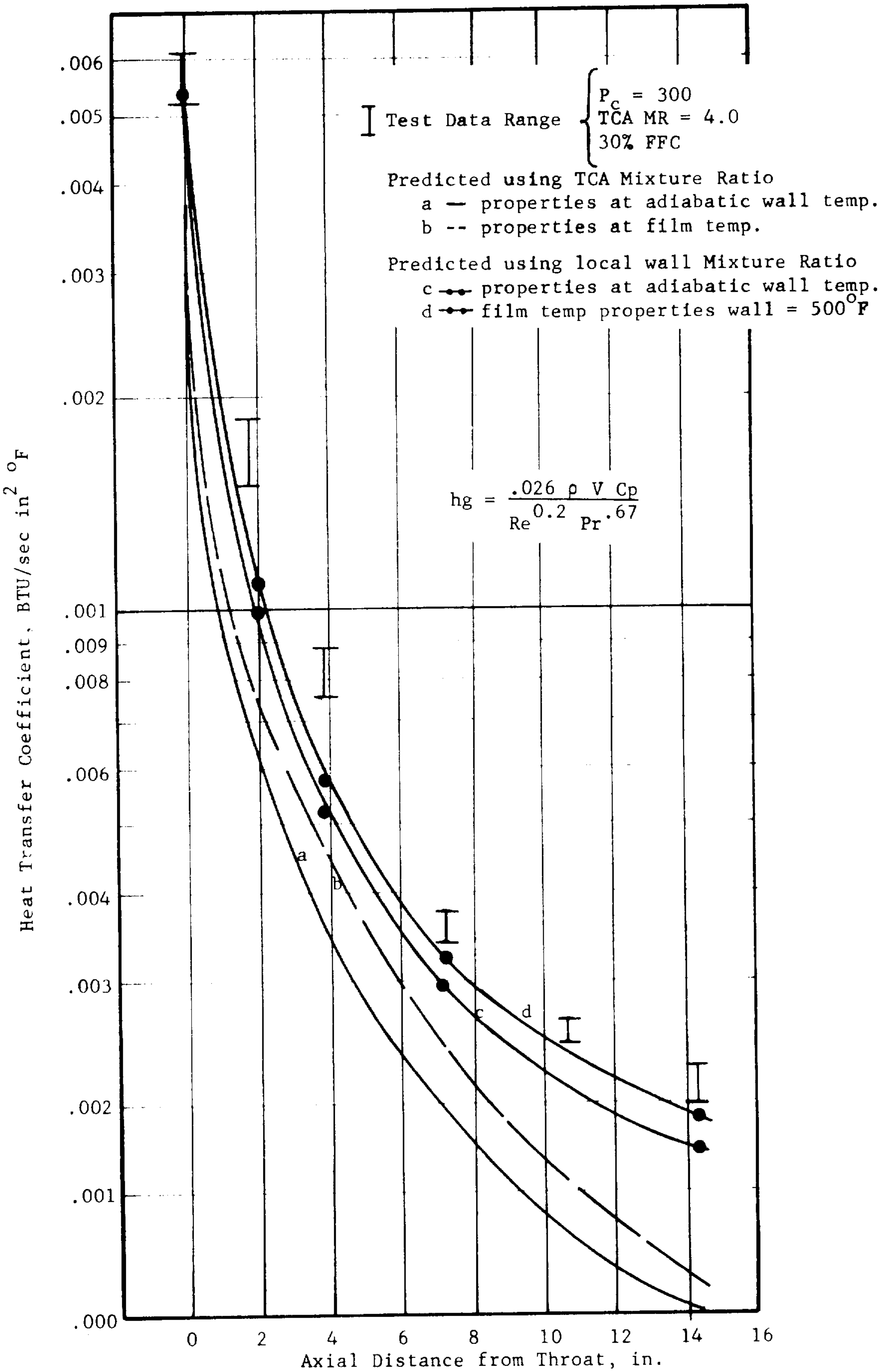


Figure 15 -- Heat Transfer Coefficients - 40:1 Film Cooled Nozzle

II,A,9,b, Summary of Testing (Series 1680-D04-0A) (cont.)

near the edge of the boundary layer for an axisymmetric Rao nozzle using the method of characteristics. Figure 16 presents the nozzle film cooling effectiveness for the same test. The effectiveness is based on measured steady-state wall temperatures corrected for radiation losses and computed on the basis that the entrained film and core flow exist in an assumed concentration distribution which is in an equilibrium chemical state. The entrainment multiplying factor (discussed in Report 14354-Q-3) indicates the mixing at the coolant injection station is 3 to 4 times greater than should be expected for optimum injection in a non-accelerating, non-turning, non-reacting situation. The high initial mixing parameter suggests improved coolant injection methods could bring about further reduction in the required film cooling flows.

10. Task X - Pulse Testing

During this report period, the constant temperature anemometer system to be used for pulse testing on Task X was checked out. Two transducers were successfully calibrated in oxygen and two were successfully calibrated in hydrogen. The calibrations were accomplished in the test circuit with each anemometer in the correct position for pulse flow. The calibrations were made with ambient temperature propellants in a five-step flow range for the purpose of linearizing the transducer output. Approximately 20 flow points were made on each anemometer. A typical analog output curve obtained during these calibrations can be found in Figure 17, which shows excellent full-scale response of approximately 10-millisecond and a minimum overshoot. It is felt that this curve represents the actual flow transient in system during the 10 millisecond valve opening and closing. During the calibrations, two anemometers' filiments were lost while hydrogen flow checks were being accomplished. One filiment appeared to be defective and the other failed at its solder joint. The calibration technique utilizing a critical nozzle

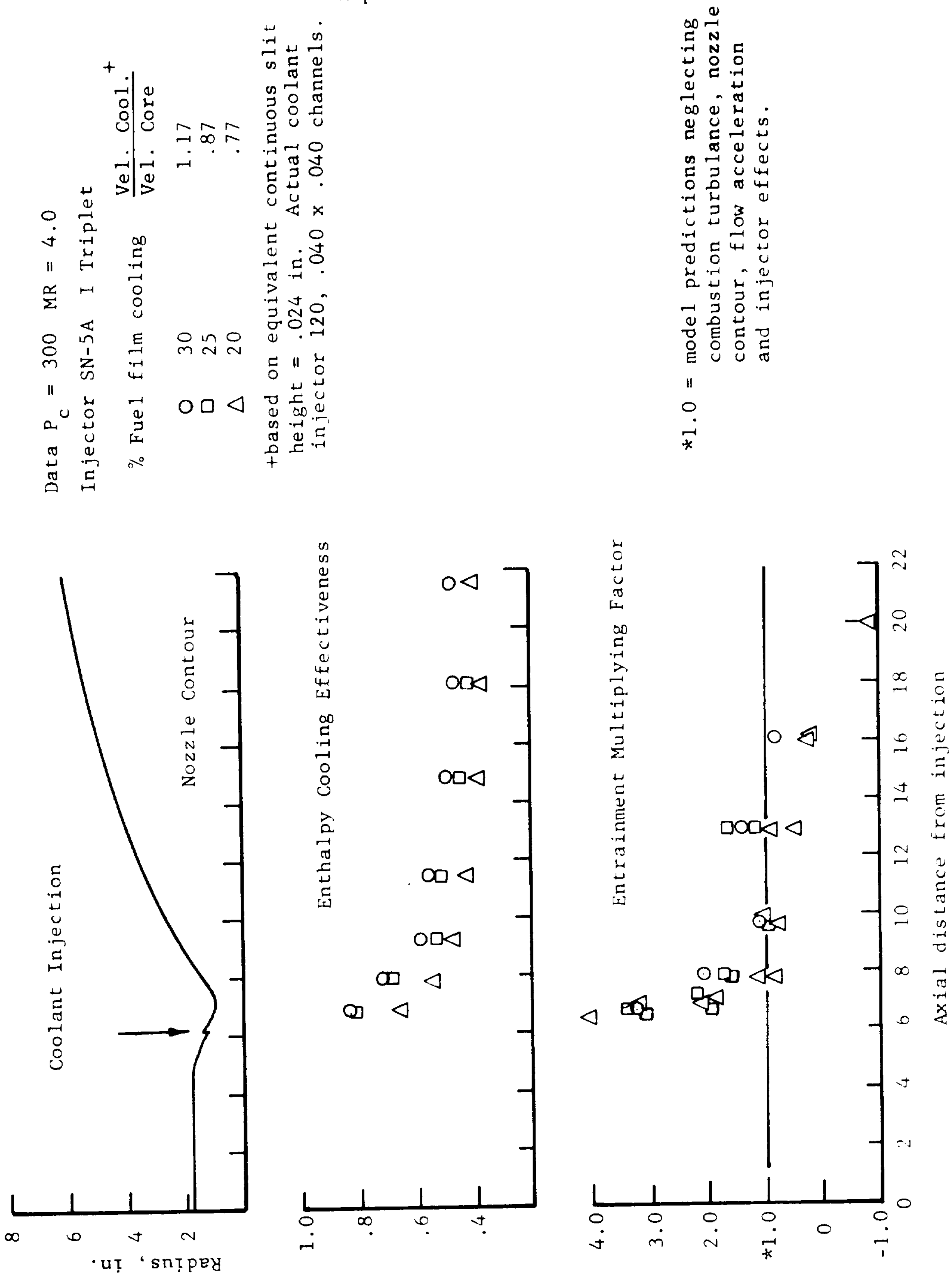


Figure 16 -- Cooling Effectiveness and Entrainment Factor
Film Cooled 40:1 Nozzle

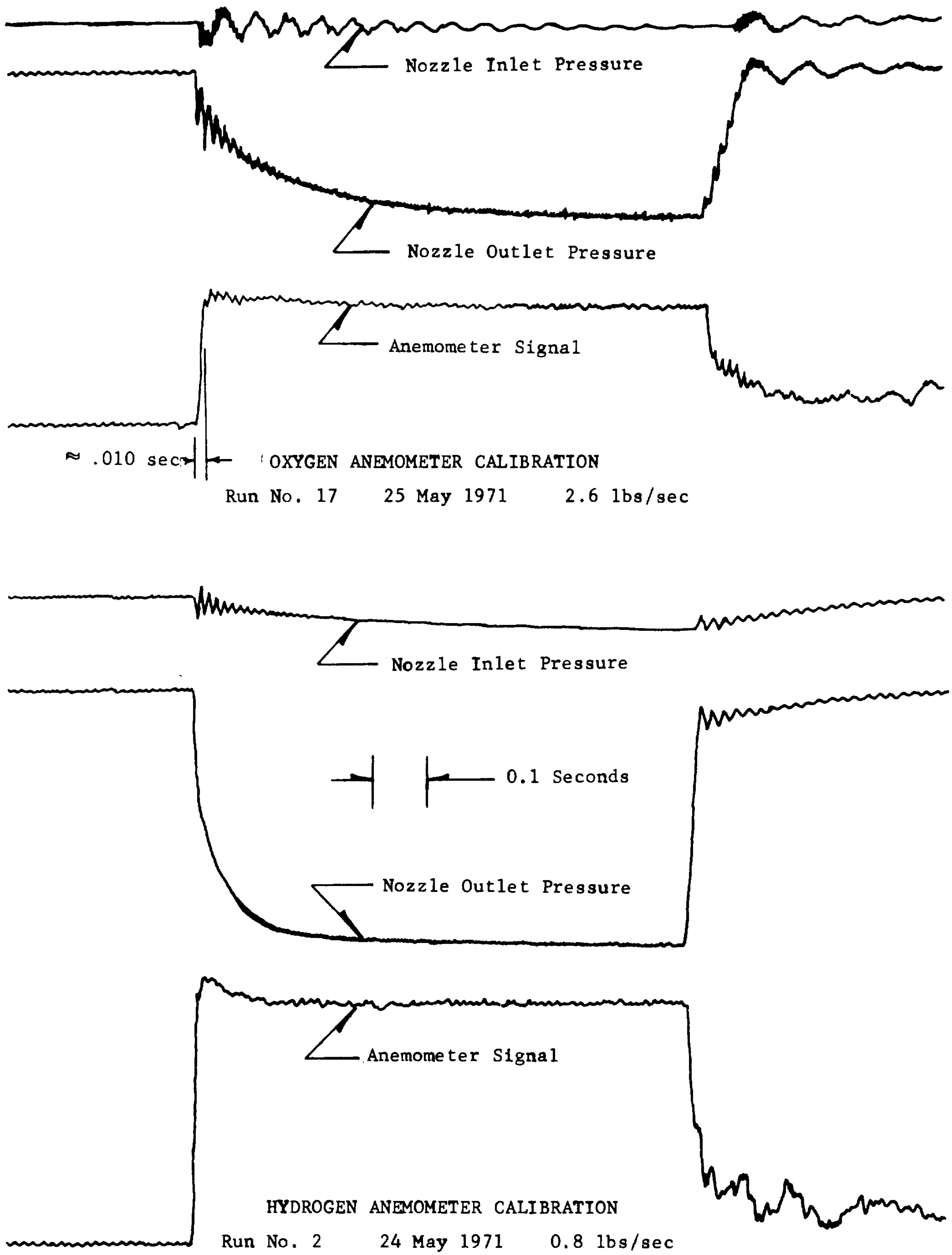


Figure 17 -- Anemometer Response and Calibration for Pulse Testing

II,A,10, Task X - Pulse Testing (cont.)

immediately upstream of the anemometer yield a higher initial pressure and thus a more severe initial flow environment than will exist during the actual pulse testing with the 17 cu. ft. accumulator between the critical nozzles and the anemometers. In addition one anemometer was damaged during installation into the propellant line. To solve these problems and to produce a less fragile transducer, four additional anemometers will be supplied by the vendor. These new transducers will have the hot film sensor .020 in. in length rather than .040 in. in length with the filiment stand-off probes shorter and stronger than the units tested. These modifications will improve the sensor strength by a factor of at least four. A special mounting/protector tool will be attached to each new transducer which will prevent any further installation or handling problems. These new transducers will be delivered during the week of 14 June 1971.

B. HIGH P_c TASKS IN REDIRECTED PROGRAM

1. Task XXII - Design of Injector for Low Temperature Propellants

Design of a new injector manifold suitable for pulsing with low temperature propellants was completed. This design is shown in Figure 18. This new manifold configuration incorporates the most successful features of both high and low P_c injector designs as established from the extensive manifold cold flow studies which were conducted in the earlier tasks. The new manifolding is designed to accommodate a bonded platelet stack containing 72 injector elements. The final pattern to be applied can be either the "I" premix triplet, a premix triplet, or any other improved pattern which can be generated by the bonded plate stack design approach. This design also allows the oxidizer orifices or tubes to be made as individual high recovery sonic venturies to give a degree of passive mixture ratio control to the injector. A second -2 assembly provides oxidizer tubes oriented in an axial rather than a canted direction. These respective designs are suitable for use

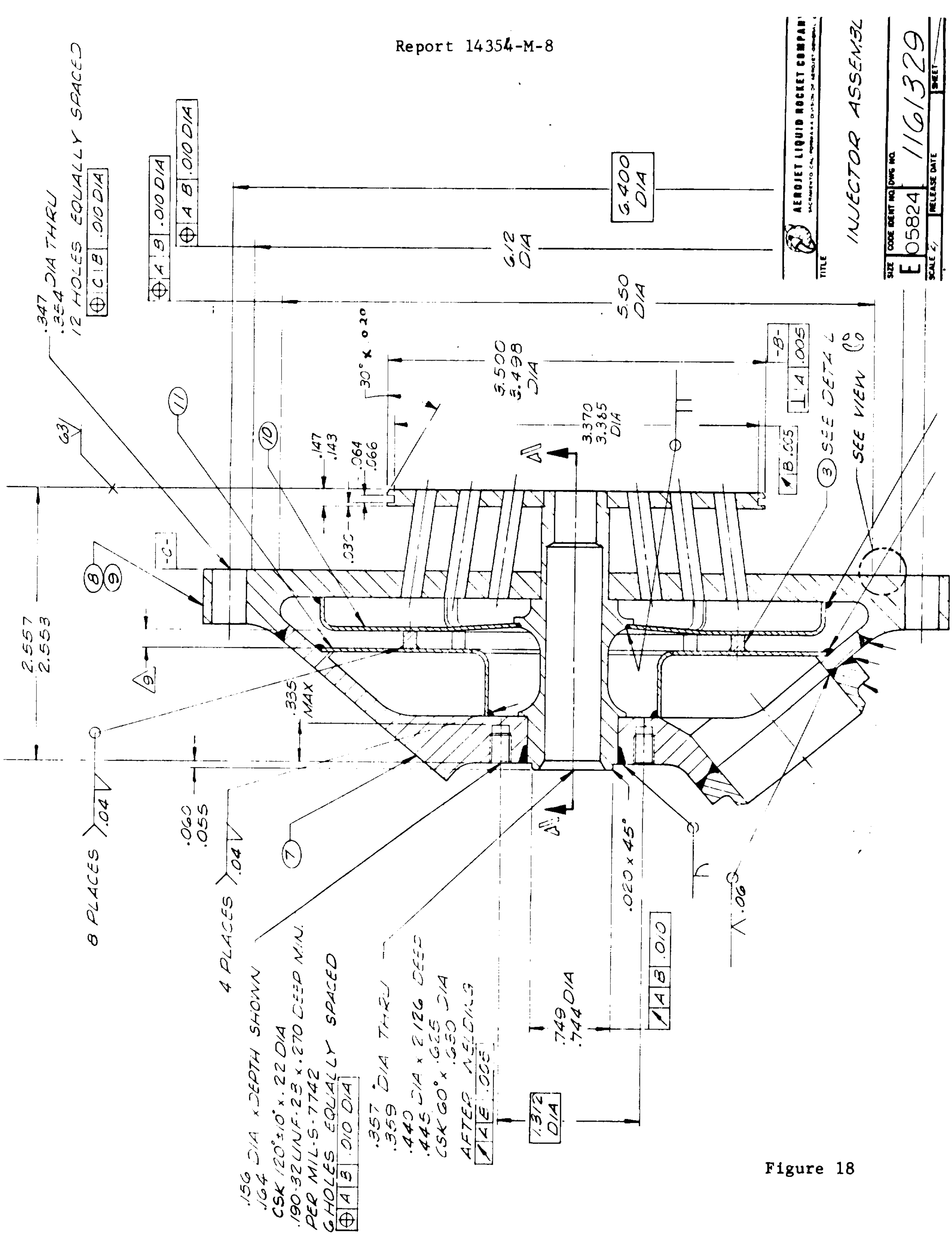

AEROJET LIQUID ROCKET COMPANY
INJECTOR ASSEMBL
05824
1161329
6.400 DIA
6.12 DIA
5.50 DIA
3.500
3.498
DIA
3.370
3.385
DIA
.347
.354 DIA THRU
12 HOLES EQUALLY SPACED
2.557
2.553
.335 MAX
.060
.055
8 PLACES
4 PLACES
.020 x 45°
.749
.744 DIA
1.312 DIA
SEE DETAIL
SEE VIEW
.156 DIA x DEPTH SHOWN
.164
CSK 120°±10° x .22 DIA
.190-32UNF-2B x .270 DEEP MIN.
PER MIL-S-7742
6 HOLES EQUALLY SPACED
.357 DIA THRU
.359
.440 DIA x 2.126 DEEP
.445
CSK 60° x .625 DIA
.650
AFTER WELDING

Figure 18

II,B,1, Task XXII-Design of Injector for Low Temperature Propellants (cont.)

in either conical or cylindrical combustion chamber contours. Design goals for this third generation design were to reduce both injector weight and volume, while at the same time providing near ideal propellant distribution through all 72 elements. The structural design criteria (per the contract requirements to obtain data at chamber pressures up to 500 psia) are as follows:

Chamber Pressure P_c = 500 psi (Nominal)
Oxidizer Manifold Pressure P_{oj} = 600 psi (nominal)
Fuel Manifold Pressure P_{fj} = 600 psi (nominal)
Proof = 700 psi

Propellant temperatures to the injector are 375°R for the oxidizer and 250°R plus coolant jacket temperature rise for the fuel.

Comparison of the Task I and Task XXII injectors are as follows:

	I	XXII
ΔP Fuel, psi	42	40
ΔP Oxidizer, psi	51	40
Weight, lbs	10	6.5
Volume (in^3) fuel	30	7.5
oxidizer	30	18.0

For flight designs an additional two pounds of weight could be eliminated if the design pressure were reduced to correspond to the nominal 300 P_c rather than 500 and the injector were welded rather than bolted to the thrust chamber. The use of materials of higher strength than CRES 304 would provide some additional weight savings.

II,B,1, Task XXII-Design of Injector for Low Temperature Propellants (cont.)

The propellant flow distribution in the oxidizer circuit, as determined from cold flow tests using GN_2, has been found to deviate less than 2% from the mean value. These data are shown in Figure 19.

2. Structural Analysis

a. Design Criteria

(1) Factor of Safety

A 1.25 factor is applied to all nominal pressures to produce limit design loads.

(2) Failure Criteria

The Huber-Von Mises-Hencky yield criterion was used as a basis for establishing the structural adequacy of the Hi P_c injector. This criterion states that when the effective stress exceeds the uniaxial yield strength of an elastic material, yielding will occur. The effective stress is computed from the following expression:

$$\sigma_{eff} = \left\{ 1/2 \left[(\sigma_1 - \sigma_2)^2 + (\sigma_1 - \sigma_\theta)^2 + (\sigma_2 - \sigma_\theta)^2 \right] \right\}^{1/2}$$

The margin of safety is:

$$M.S. = \frac{\sigma_{allow}}{\sigma_{eff}} - 1$$

where, σ_1 = Principal stress in the radial direction

σ_2 = Principal stress in the Z direction

σ_θ = Circumferential (hoop) stress

σ_{allow} = Uniaxial material allowable

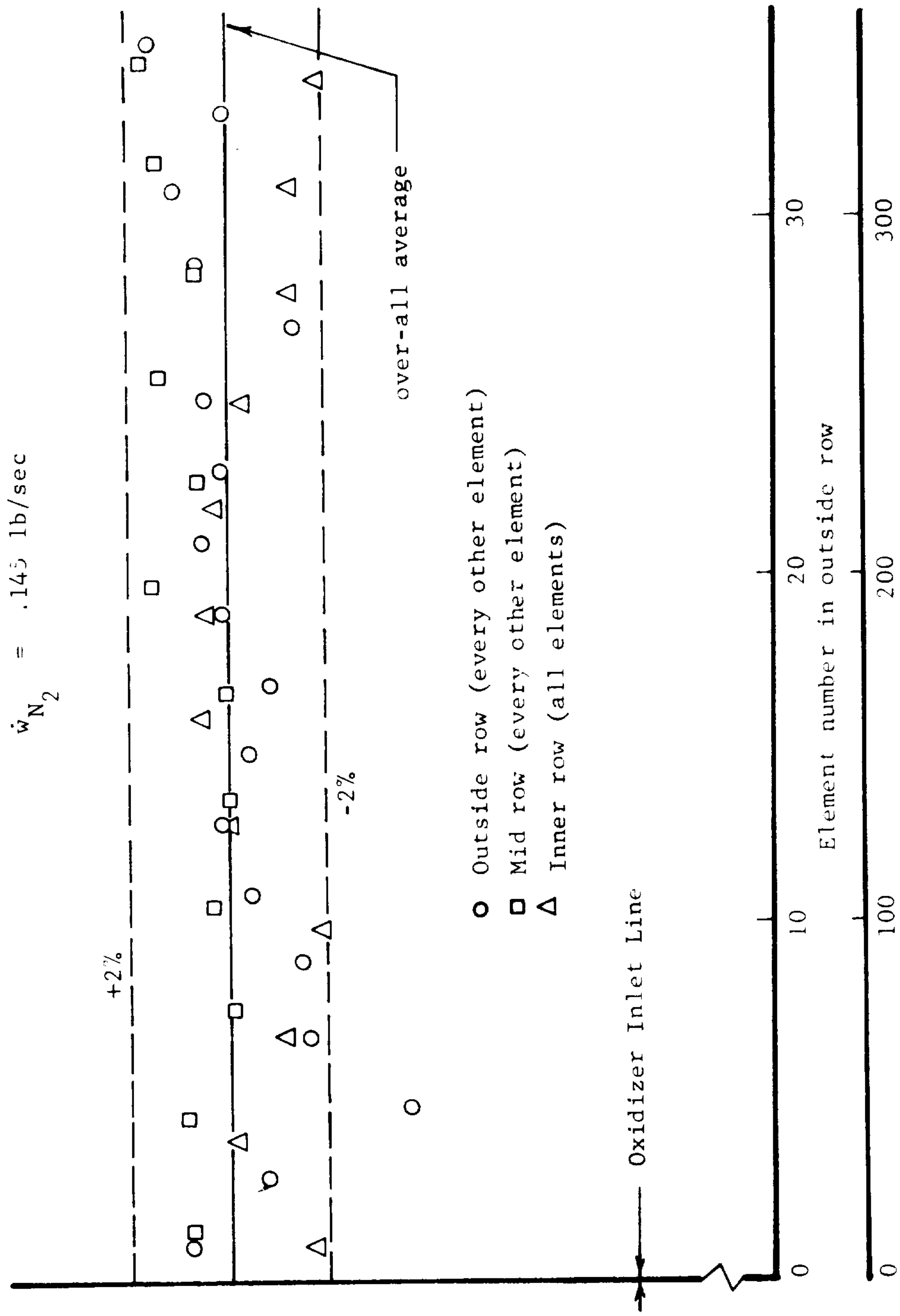


Figure 19 -- Oxidizer Flow Distribution Premix Injector with GN_2

II,B,2, Structural Analysis (cont.)

Fatigue life of a component is established by comparing the total maximum strain to an S-N curve of the particular material.

b. Materials

All components are annealed type 304 Stainless Steel except the face platelet stack which is annealed Nickel 200.

Type 304 Stainless Steel

F_{tu} = 75000 psi
F_{ty} = 30000 psi
$E = 29.0\ (10^{6})$ psi
$\mu = .30$
$\alpha = 9.2\ (10^{-6})$ in./in./^{o}F

Nickel 200

	R.T.	600^{o}F	1200^{o}F
F_{tu}	67000	66200	21500
F_{ty}	21500	20300	10000
E	$30.(10^{6})$	-	-
μ	.3	.3	.3
α	$7.4\ (10^{-6})$	$8.0\ (10^{-6})$	$8.7\ (10^{-6})$

3. Method of Analysis

The structural components of the Hi P_c injector was analyzed as a figure of revolution loaded by pressure. To facilitate the analyses the injector geometry was introduced to the AB5U Computer Program. This program is a finite element stress analysis of axisymmetric and plane structures.

II,B,3, Method of Analysis (cont.)

The model shown in Figure 20 was introduced to three different loading conditions which correspond to the three possible operating modes. These modes are: (1) proof pressure in the chamber with the injector used as a closure (no ΔP across the face or injector plate), (2) oxidizer lead with full pressure in the oxidizer manifold and zero pressure in the fuel cavity and chamber, and (3) fuel lead with full pressure in the fuel manifold while pressure is zero in the chamber and oxidizer manifold.

In all cases the injector is fixed against axial deflection and rotation at the bolt circle.

The platelet stack attached to the injector face is subjected to rather steep temperature gradients which in turn force the material well into the plastic range. The maximum thermal strains are determined by:

$$\epsilon_{max} = \alpha \Delta T$$

where: α = Coefficient of thermal expansion

ΔT = Temperature gradient

This relationship is for a plate that is fully restrained while exposed to a temperature gradient.

Fatigue life of the face is based on a comparison between the calculated maximum thermal strains and an empirically derived S-N curve for the material.

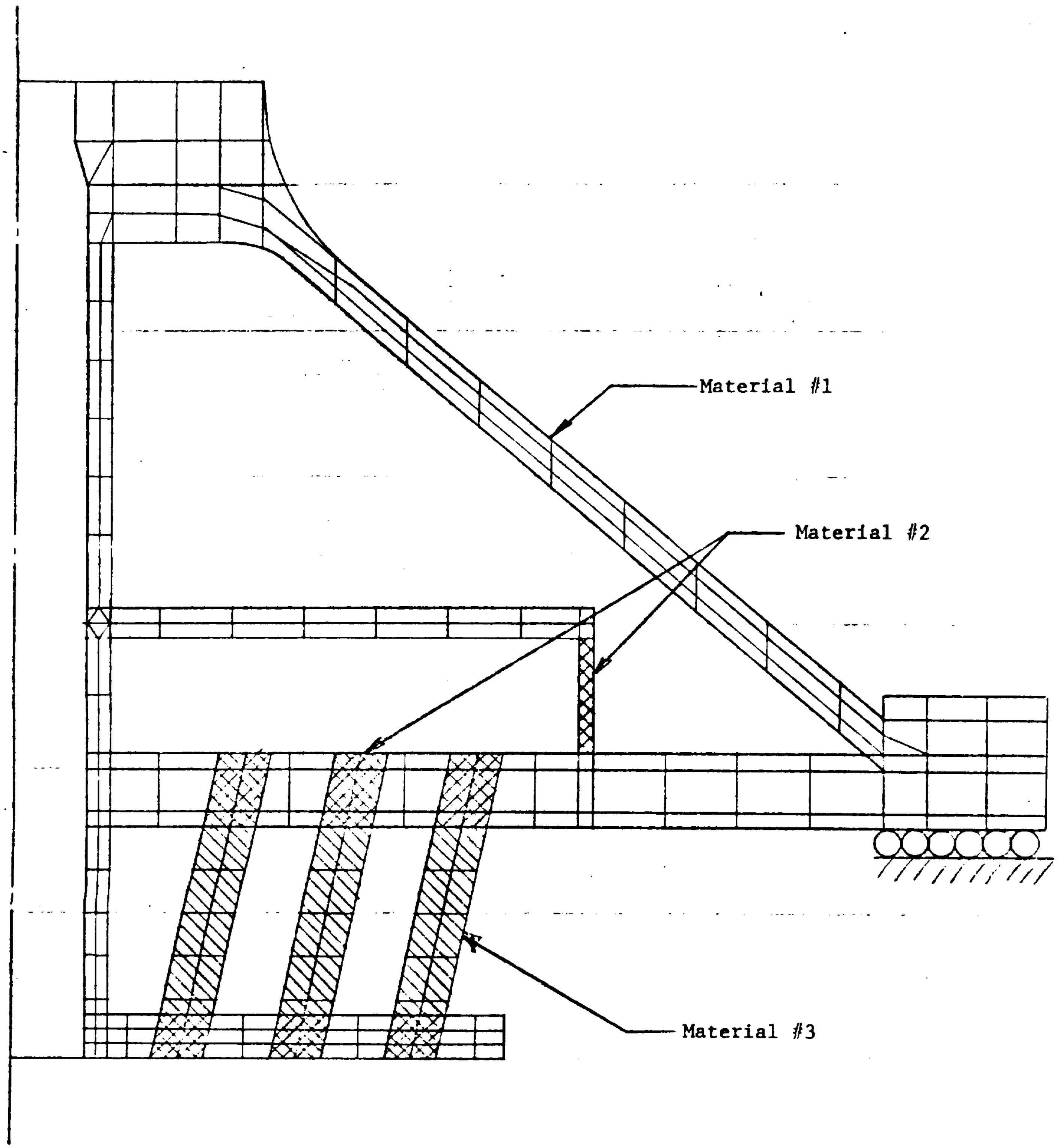


Figure 20 -- Computer Representation of the High Chamber Pressure Injector

II,B, High P_c Tasks in Redirected Program (cont.)

4. Results of Analysis

a. Pressure Strains

The design shown in Figure 18 operates in the elastic material range throughout. The maximum stress at the most severe proof or over-pressure conditions is 83% of the material yield strength at $70^{\circ}F$. Under normal 300 P_c cyclic operation, maximum stress is 42% of yield (.044% strain), thus insuring a pressure cyclic life > 10^6.

b. Thermal Strains

The orifice pattern on the face is such that when the fuel impinges on the oxidizer a fan shaped flame is produced. This flame in turn impinges on the 200 Nickel platelet face causing a local surface hot zone. Thermocouples located on the injector face during firings with various element configurations have shown that the local face temperature can be maintained at fuel temperature plus $200^{\circ}F$ to fuel temperature plus $800^{\circ}F$, depending on the pattern design selected.

The analysis assumes the cold side of the bonded nickel face platelets is stressed in tension while the hot side is in compression. The back-side of the platelet face is not only at propellant temperature but is also held at approximately zero strain by the relatively heavy steel face plate. The strain on the hot face for the fully restrained condition then is:

$$\epsilon_{max} = \alpha \Delta T$$

II,B,4, Results of Analysis (cont.)

c. Fatigue Life

Figure 21 shows the relationship between total strain and fatigue life for Type 200 Nickel at 70°F and 600°F. Both curves fall on one line reflecting the material's insensitivity to temperature in this range. However, for temperatures in excess of 600°F, the mechanical properties fall off rapidly and a significant deterioration of fatigue life can be expected. A data point from a RPL test at 1400°F and an estimated fatigue life curve at 1400°F is also shown on Figure 21 and can be used to bracket the fatigue life for temperatures above 600°F.

ΔT	ϵ_{max}	N_f
0	0	∞
200	.148%	$> 10^6$
400	.308%	$50.0(10^3)$
600	.480%	$11.0(10^3)$
800	.655%	$5.6\ (10^3)$
1000	.850%	$(.9 \text{ to } 3.0)(10^3)$

Figure 22 shows the relationship between fatigue life and temperature gradient across the face.

TASK XXIII Injector Fabrication

During this report period machining was completed for components for two injector assemblies. The first unit was assembled via standard brazing and electron beam welding techniques, as shown in Figure 23. Remaining operations are bonding of the face platelets containing the fuel pattern and welding of the osidizer inlet lines. The second set of components is being held in a dis-assembled state pending final assembly and checkout of the first unit.

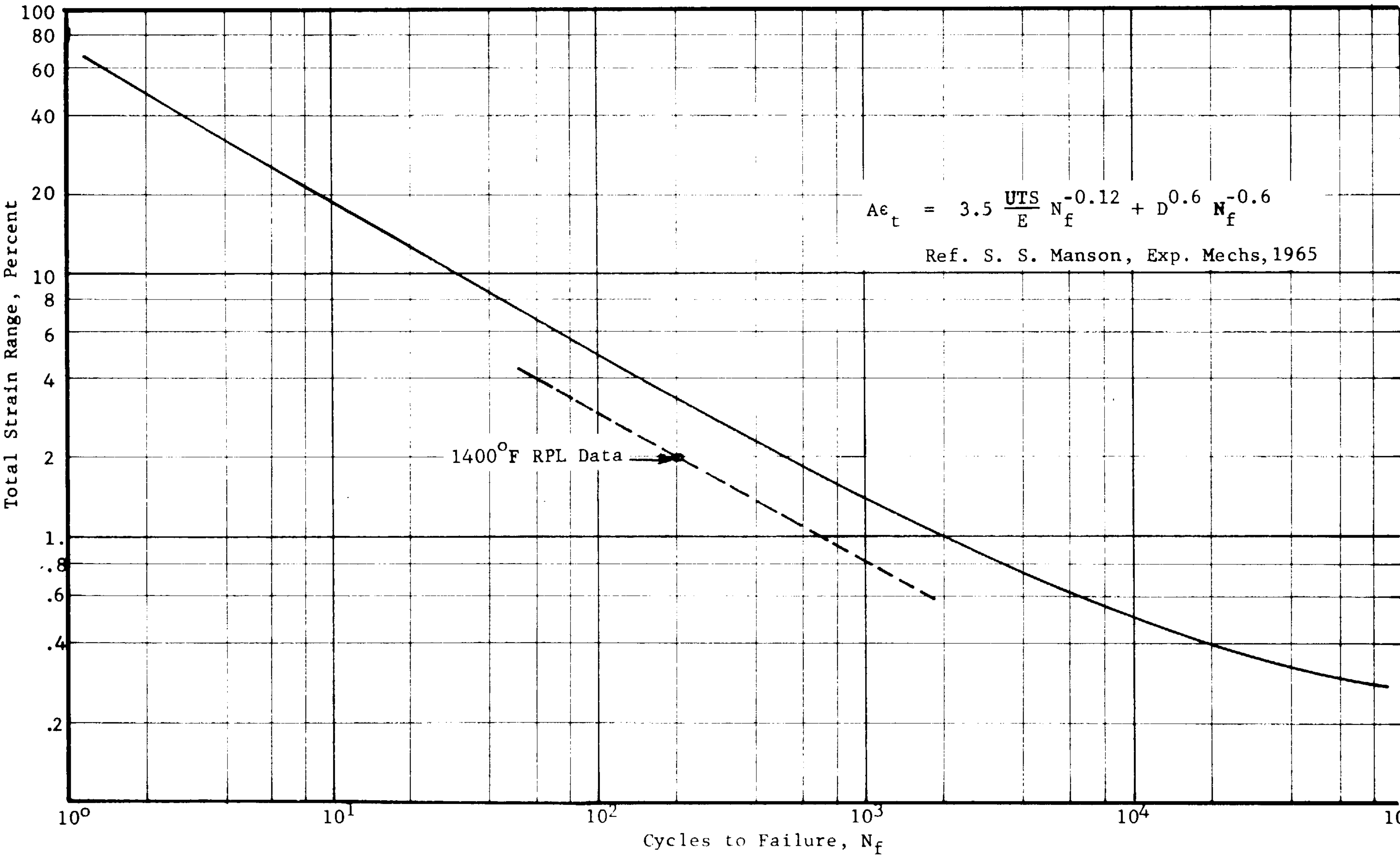
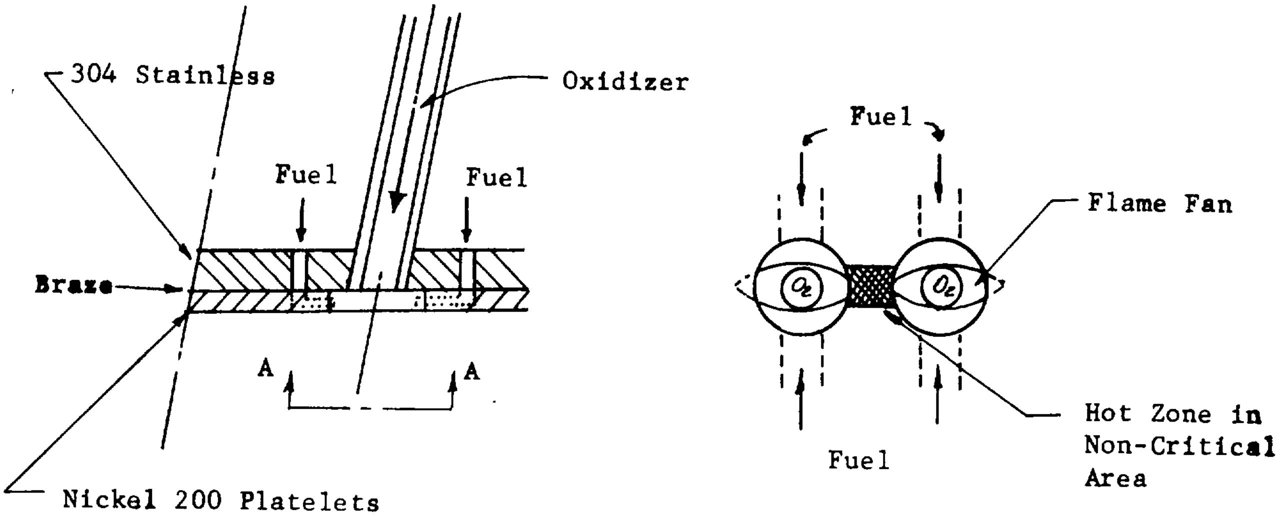


Figure 21 -- Fatigue Life vs. Total Strain Range for Nickel 200 at 70°F and 600°F



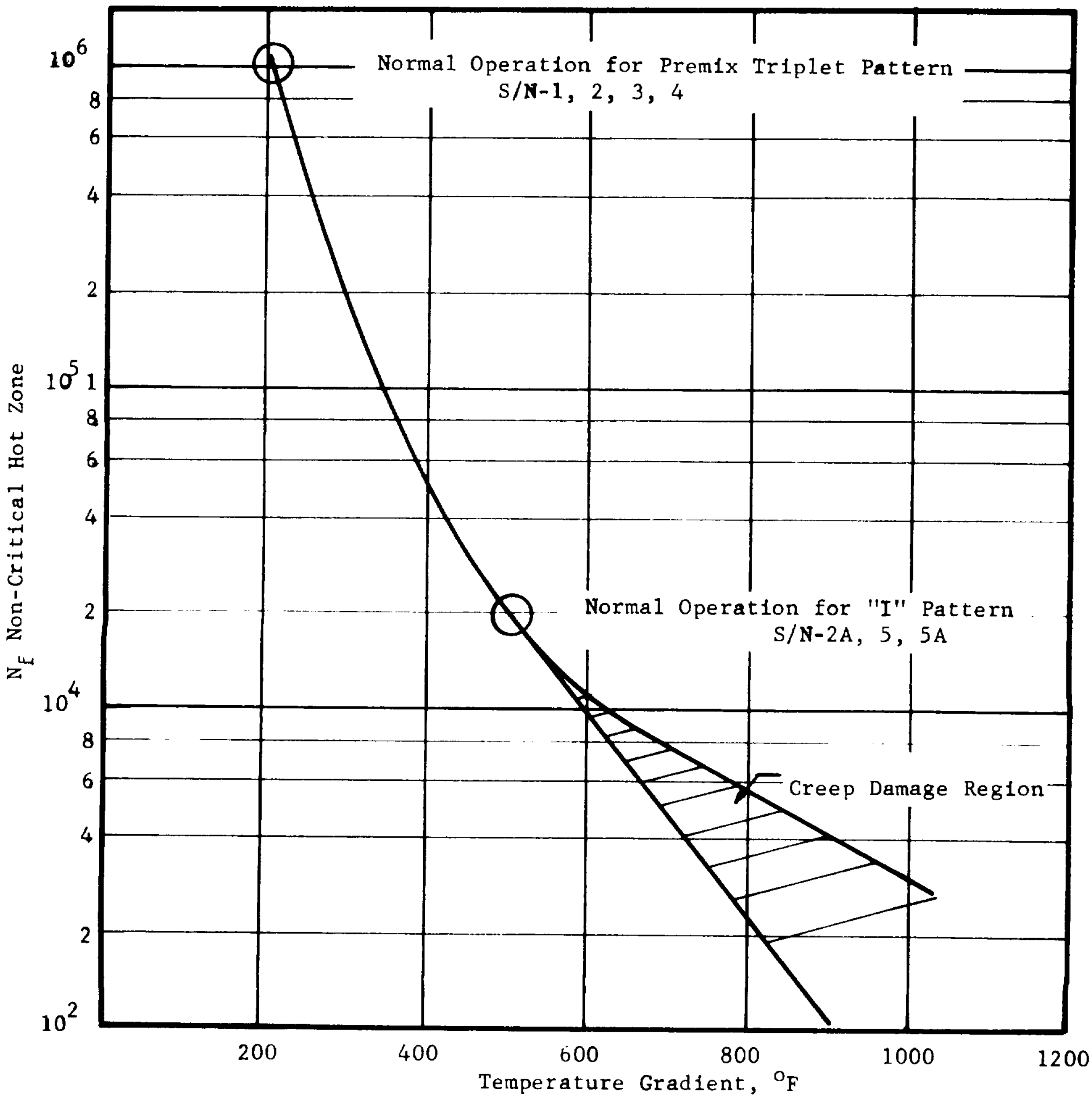


Figure 22 -- Fatigue Life vs. Temperature Gradients for Platelet Injector Face

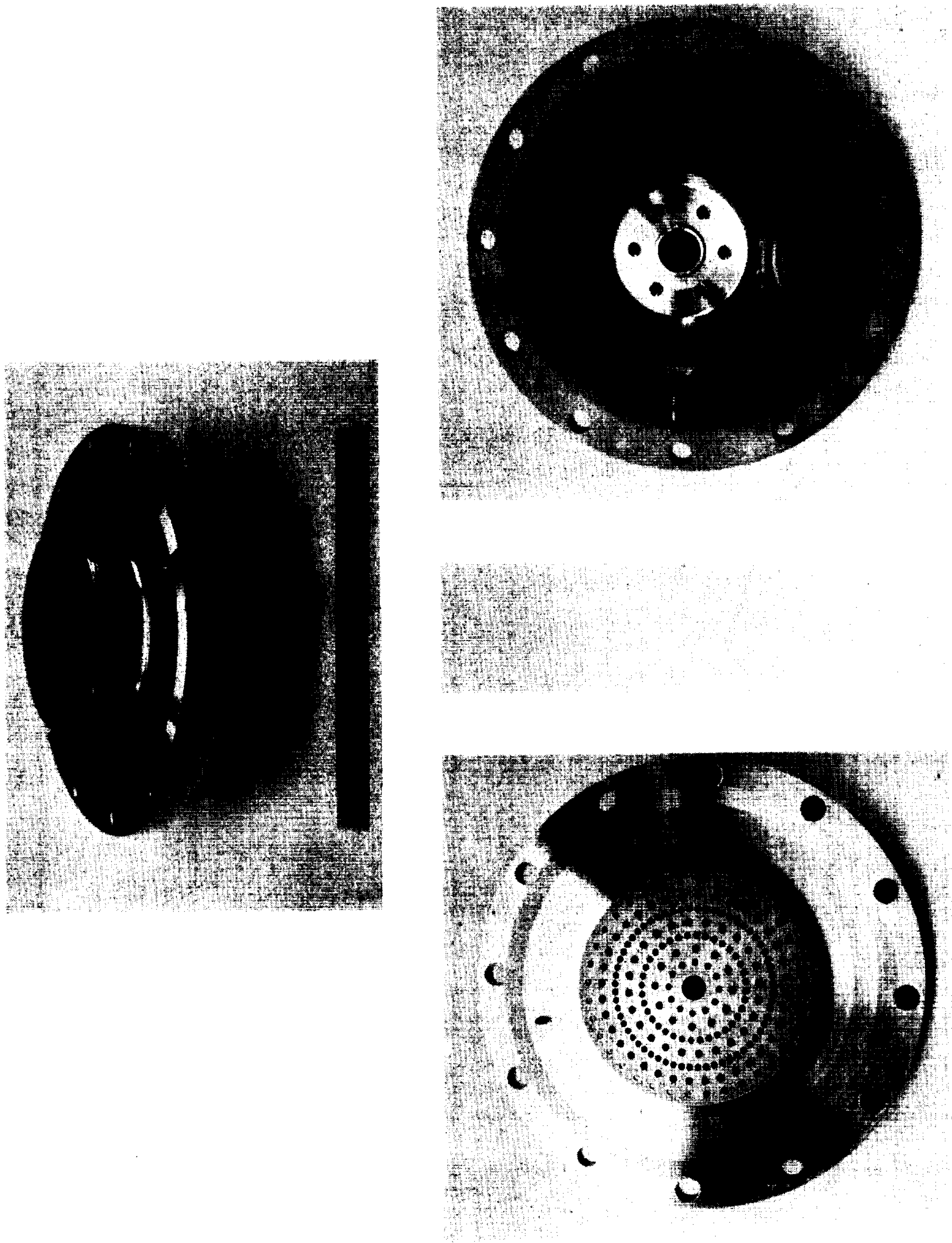


Figure 23 -- 72-Element Injector Manifolding Before Face Plate Bonding

II,B,4, Results of Analysis (cont.)

TASK XXIV Cooled Chamber Analysis and Design

The technical objectives of this task are as follows:

1. Reoptimize the manifolding and coolant channel geometry of Task III film cooled and regeneratively cooled chamber designs to reflect the revised propellant temperature schedules.

2. To design a film cooled nozzle skirt suitable for use with either above design which is capable of operation at temperatures in excess of 2000°F.

3. To generate one new chamber design in which primary emphasis is placed on achieving minimum weight and the ability to withstand long exposure to a 2000°F re-entry heating environment.

Design modification in the first objective category involve a reduction of both manifold and coolant channel cross-sectional areas to be compatible with the higher density propellants. Design modifications are also being made to integrate data acquired in fabrication, cold flow and hot fire tests conducted in the first 10 program tasks. Each of these new designs also will evaluate floating manifolds which accommodate relative movement of the thermally contracting manifold, and expansion to the hot inner wall. Activities in this task have proceeded to the point where: (1) the channels have been resized for both designs and optimized for the high re-entry temperature design; (2) structural analyses of these designs including the floating manifolds is now in progress; and (3) the high temperature skirt materials evaluation has been completed.

II,B,4, Results of Analysis (cont.)

Results of these activities are as follows:

In the new lightweight chamber design study, the use of copper is excluded at all locations since the melting temperature of this material is less than the 2000°F re-entry heating condition. The designs being investigated build off the successful fabrication and test experience of the nickel/steel film cooling rings used in Task VIII and the film cooled Haynes 188-stainless steel 40:1 nozzles demonstrated in Task IX.

Lightweight High Temperature Material Design

The new design employs a parallel flow dump cooling arrangement in a conical 5.5-in. L' combustion chamber. Based on Task IX test results, 20% of the fuel is used to convectively cool a 3-in. long slotted and bonded nickel ring. The coolant discharging from the ring is capable of film cooling the nozzle to any area ratio. A smaller amount of additional film cooling is provided from the injector face to obtain the desired cyclic life of the nickel ring and coolant pressure drop. Figure 24 shows the final results of a comprehensive parametric analysis which optimized the length, materials, number and size of coolant channels, and coolant flow in the convectively cooled section. The optimized wall configuration contains 160 coolant channels .025 in. deep, .030-in. wide, within a .080-in. thick composite nickel/steel wall. The upper left plot in Figure 24 shows the maximum wall temperature at nominal design conditions vs. percent face plane injected coolant, for various dump ring lengths, with a constant 20% fuel flow through the ring. The maximum gas-side nickel wall temperature for a 3-in. length can be selected to fall between 400°F and 950°F as the face plane coolant is reduced from 10% to 0. The resulting inside to outside thermal gradients (which dictate chamber life) correspondingly vary from 300°F at the maximum flow to 660°F at 0 face plane coolant injection. The corresponding pressure drop characteristics and injection velocities are shown in the lower two figures. The final selection of face

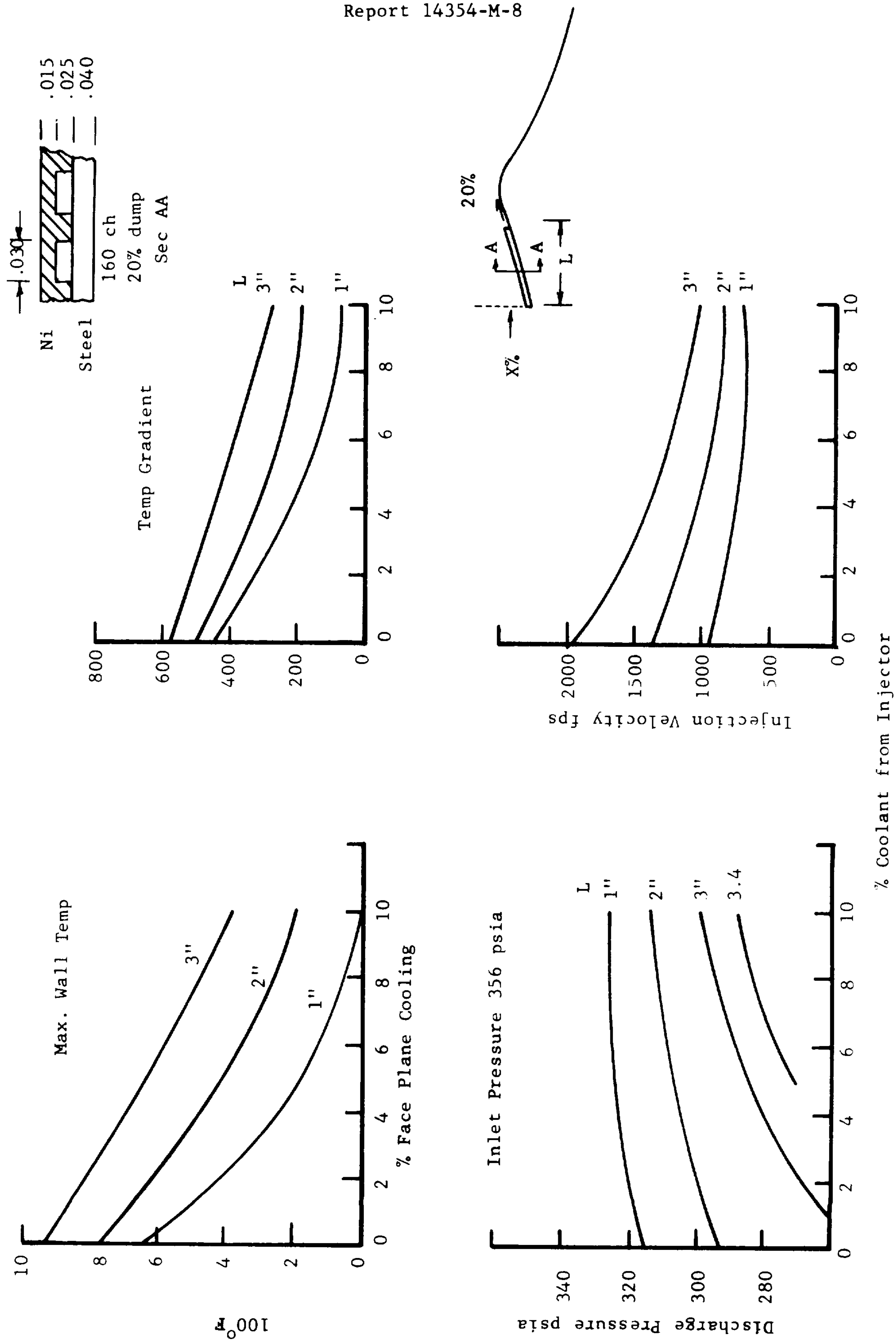


Figure 24 -- Film Cooled Conical Chamber Steady-State Temperatures

II,B,4, Results of Analysis (cont.)

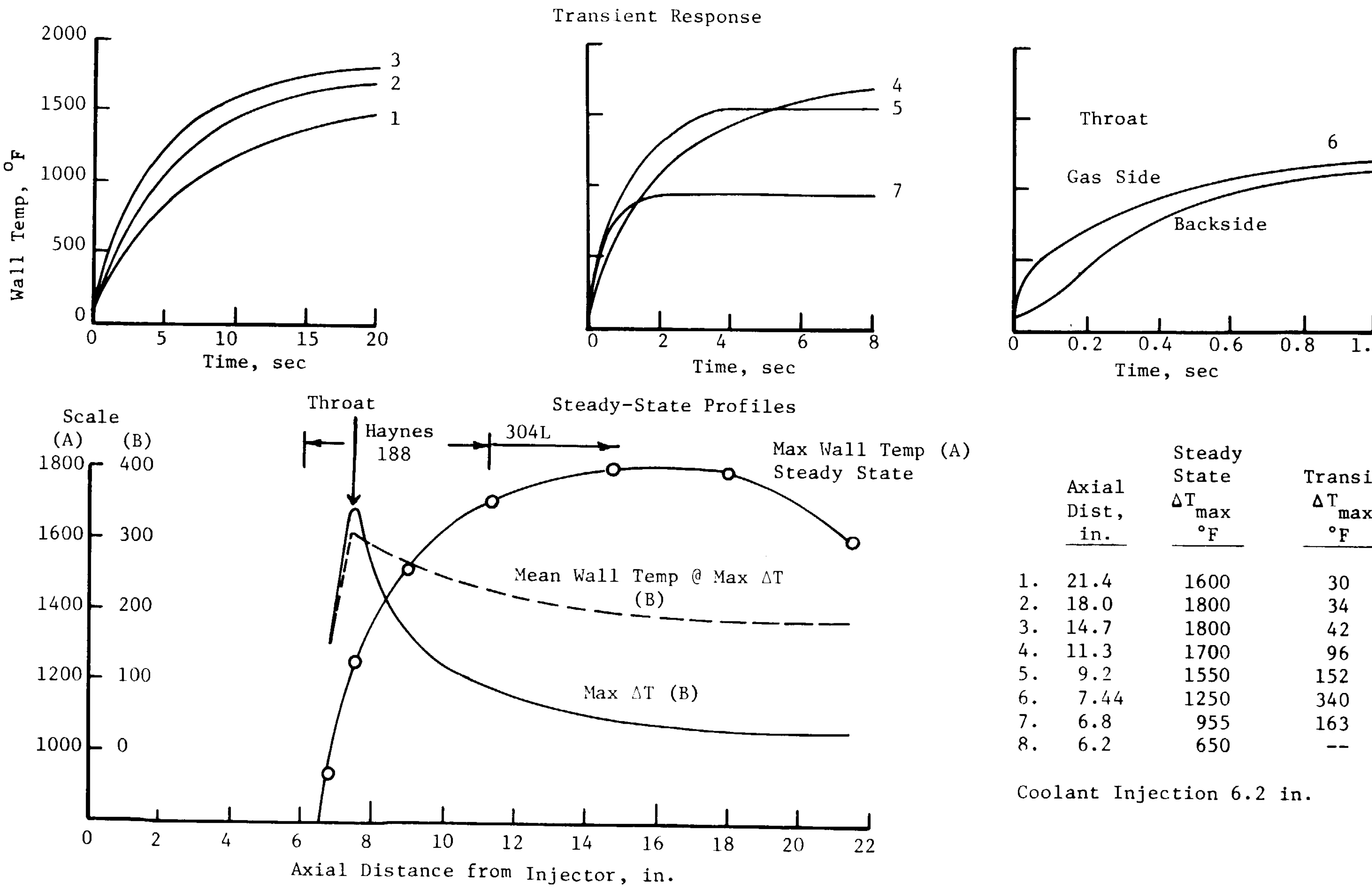
plane cooling will be dictated by cyclic life and pressure drop consideration. The second portion of the analysis which applies to the region downstream of the dump is shown in Figure 25. This figure provides the basis for the thermal/stress analysis as it contains both the transient and steady-state temperature gradients. The parameters generated in this figure are derived for a nozzle wall which is .040-in. thick from the coolant injection point to 40:1 area ratio, using the experimental heat transfer coefficients and recovery temperatures from test 015 in Task IX. The plot shows axial temperature gradients at steady-state, radial temperature (ΔT max.) during transient and the wall heating rate at eight locations. Maximum throat strains are developed at approximately .05 seconds after fire switch, however, only when the chamber wall is cold. If the engine is pulsing rapidly and the wall is at near steady-state temperatures, thermal gradients and resulting strains will be reduced considerably. Current structural analyses are being conservatively conducted on the basis of the number of cold starts.

Full high temperature thermal cycles do not appear to be a problem in the skirt because of slow heating rates ($200^{\circ}F$/sec vs. $2000^{\circ}F$/sec in the throat) and the 50-hour chamber life requirements. The 50-hour limit would be accumulated after only 18,000 10-sec firings assuming the wall was cold each time the chamber was fired. The $42^{\circ}F$ ΔT realized when the wall is cold results in nearly unlimited life.

Regeneratively Cooled Chamber Design

The Task VIII test data showed that to obtain the life goal of 100,000 full thermal cycles with the regeneratively cooled design would require more film cooling than is required with the film cooled design. These data and predictions are summarized as follows:

0.040 in. Haynes/304 Nozzle
MR = 4, 19% Film Cooling



	Axial Dist, in.	Steady State ΔT_{max} °F	Transient ΔT_{max} °F
1.	21.4	1600	30
2.	18.0	1800	34
3.	14.7	1800	42
4.	11.3	1700	96
5.	9.2	1550	152
6.	7.44	1250	340
7.	6.8	955	163
8.	6.2	650	--

Coolant Injection 6.2 in.

Figure 25 -- Film Cooled Nozzle Thermal Profiles based on Data Test 1680-D03-0A-015

II,B,4, Results of Analysis (cont.)

Film Coolant Injection at Face Plane

% FC	T Wall, °F	Heat Flux, BTU/sec in^2	Projected* I_s vac, sec	Throat N_f (thermal) Zirconium Copper
0	820	12	450	5000
20	800	11.8	440	6000
30	600	8.0	430	13000

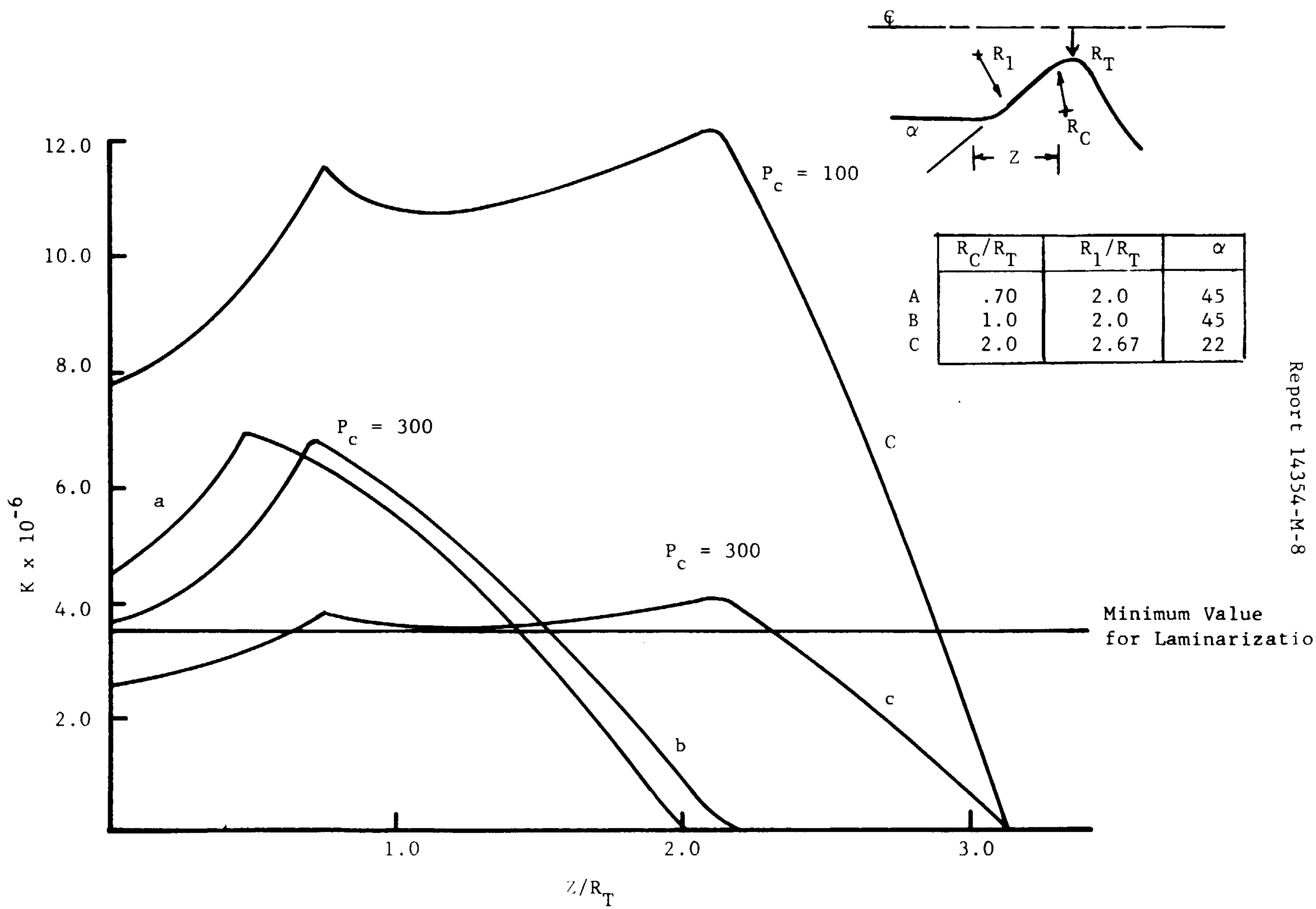
Film Coolant Injection 2-1/2 in. Downstream of Face

% FC	T Wall, °F	Heat Flux, BTU/sec in^2	Projected* I_s vac, sec	Throat N_f (thermal) Zirconium Copper
20	630	8.7	440	11000
30	530	5.7	430	40000

*Based on Task VIII and Task IX test results with "I" triplet injector.

An alternate approach to reducing the heat flux which is being considered, is to modify the contour in an attempt to increase the throat pressure gradient and relaminarize the boundary layer. If a laminarized boundary layer could be achieved, the 0% film cooling throat heat flux could be as low as 6.6 BTU/sec in^2. The peak flux upstream of the throat is 7.8 BTU/sec in^2. Figure 26 shows the K parameter for laminarization as suggested in Ref. 1.

Ref. 1 Moretti, P.M., Kays, W.M., Heat Transfer to a Turbulent Boundary Layer with Varying Free Stream Velocity and Surface Temperature, Int. J. Heat and Mass Trans., Vol. 8, 1965



	R_C/R_T	R_1/R_T	α
A	.70	2.0	45
B	1.0	2.0	45
C	2.0	2.67	22

Figure 26 -- Criteria for Laminarization of the Regeneratively Cooled Chamber

II,B,4, Results of Analysis (cont.)

Complete laminarization is possible when

$$K = \frac{\mu}{\rho\ u} \left[\frac{1}{u} \frac{du}{dx} + 0.4 \frac{1}{r} \frac{dr}{dx} \right] \geq 3.3 \times 10^{-6}$$

μ = viscosity

ρ = density

u = freestream velocity

r = local chamber radius

x = contour length

Figure 26 shows the magnitude of the K parameter for several convergent nozzle contours at 100 and 300 psia. Contour C was employed in Task VIII testing which demonstrated the reduced heat transfer ratio associated with a laminarized condition at 100 psia but not at 300 psia. This is consistant with the prediction criteria shown in Figure 25, which suggests the 300 psia condition is very marginal. Modification of the contour could bring about a two-fold increase in the K parameter for 300 psia operation and significantly improve the chance of a laminarized boundary layer at the throat.

The potential of employing or demonstrating this phenomena as a means of extending chamber life and without film cooling is being evaluated.

TASK XXV Cooled Chamber Fabrication

Fabrication was initiated on the Haynes 188 throat and skirt for the new film cooled chamber for this task.

TASKS XXVI - XXVIII

No activity.

III. WORK DURING NEXT REPORTING PERIOD

Tasks I through VIII - no activity.

Task IX - Continue cooled chamber testing and evaluate test data. Install and check out new facility heat exchangers.

Task X - Finalize Test Plan, flow control and flow measuring procedures. Calibrate new anemometers.

Task XXII - Finalize face plate pattern of injector for film cooled design and cold flow both circuits for distribution efficiency.

Task XXIII - Complete fabrication of first new low propellant temperature injector.

Task XXIV - Continue design modification efforts of chambers for low temperature propellants. Complete detailed thermal and structural and life analyses.

Task XXV - Initiate fabrication of second generation film cooled chamber with revised coolant channels on floating manifolding.

IV. PROBLEM AREAS

There are no significant technical problems. The testing is proceeding slower than planned because of facility delays in getting thinner heat exchangers into the system, however this should be cleared up in the next few weeks.

FORECAST AND CONSUMPTION OF GOVERNMENT-FURNISHED PROPELLANTS

Contract NAS 3-14354

Material	Monthly Usage	Cumulative	Next Month's Requirements	Next 3 Month Requirements
LO_2 (ton)	23	23	11	180
LH_2 (lbs)	0	7210	3300	14,200
LN_2 (ton)	48	311	150	375
GHe 10^3 (SCF), Bulk	0	99,100	12.5	25
GHe 10^3 (SCF), Cylinders	0	0	19	7

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Lewis Research Center

CONTRACT PROGRESS SCHEDULE

REPORT FOR MONTH ENDING: 30 May 1971

FORM APPROVED. BUDGET BUREAU NO. 104-R0007

1. CONTRACT TITLE: Hydrogen-Oxygen APS Engines (High P_c)

2. CONTRACTOR (Name and address): Aerojet Liquid Rocket Co., P.O. Box 13222 Sacramento, California 95813

3. CONTRACT NO.: NAS 3-14354

4. APPROVED (Contractor's Project Manager): L Shoenman

PREPARATION DATE: 6-10-71

5. NASA APPROVED SCHEDULE DATE: 8-31-70

9. NASA Use Only — a. NASA CODE; b. PROJECT MGR.; c. EVALUATION DATE; d. EXCEPTION CATEGORY; e.; f.; g.

Task	6. REPORTING CATEGORY	7. 1970: J A S O N D — 1971: J F M A M J J	8. TECH. OBJECTIVE % COMP.	e.	f.	g.
I	Injector Analysis and Design		100			
II	Injector Fabrication		100			
III	Thrust Chamber Analysis and Design		100			
IV	Thrust Chamber Fabrication		95			
V	Ignition System Analysis and Design		100			
VI	Ignition System Fabrication and Checkout		100			
VII	Bipropellant Valve Preparation		100			
VIII	Injector Tests		100			
IX	Thrust Chamber Cooling Tests		35			
X	Pulsing Tests		1			

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CONTRACTOR'S WORKING SCHEDULE

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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CONTRACT PROGRESS SCHEDULE

REPORT FOR MONTH ENDING: 30 May 1971

FORM APPROVED. BUDGET BUREAU NO. 104-R0007

9. NASA Use Only — a. NASA CODE — b. PROJECT MGR. — c. EVALUATION DATE — d. EXCEPTION CATEGORY (e. f. g.)

1. CONTRACT TITLE: Hydrogen-Oxygen APS Engines (Low P_c)

2. CONTRACTOR (Name and address): Aerojet Liquid Rocket Company, P.O. Box 13222 Sacramento, California

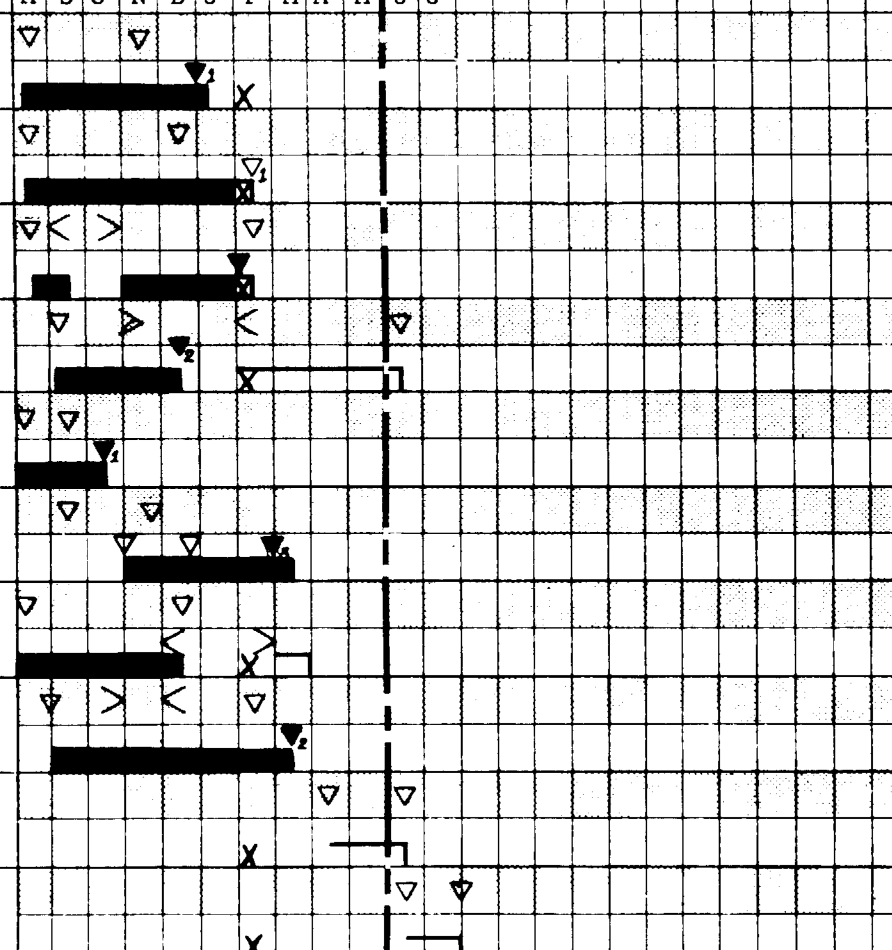
3. CONTRACT NO.: NAS 3-14354 Amendment I

4. APPROVED (Contractor's Project Manager): R. A. Dane

PREPARATION DATE: 6-10-71

5. NASA APPROVED SCHEDULE DATE: 8-31-70

7. 1970 / 1971: A S O N D J F M A M J J



Task	6. Reporting Category	8. Tech. Objective % Comp.
XI	Injector Analysis and Design	100
XII	Injector Fabrication	100
XIII	Thrust Chamber Analysis and Design	100
XIV	Thrust Chamber Fabrication	100
XV	Ignition System Analysis and Design	100
XVI	Ignition System Fabrication and Checkout	100
XVII	Bipropellant Valves Preparation	100
XVIII	Injector Tests	100
XIX	Thrust Chamber Cooling Tests	100
XX	Pulsing Tests	100

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CONTRACTOR'S WORKING SCHEDULE

X Indicates activities halted by stop work order dated 11 February 1971.

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CONTRACT PROGRESS SCHEDULE

REPORT FOR MONTH ENDING: 30 May 1971

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1. CONTRACT TITLE: Hydrogen-Oxygen APS Engines

2. CONTRACTOR (Name and address): Aerojet Liquid Rocket Company, P.O. Box 13222 Sacramento, California 95813

3. CONTRACT NO.: NAS 3-14354

4. APPROVED (Contractor's Project Manager): R J La Bot

PREPARATION DATE: 6-10-71

5. NASA APPROVED SCHEDULE DATE: 8-31-70

6. REPORTING CATEGORY	7. 1970 J	A	S	O	N	D	1971 J	F	M	A	M	J	J	A	S	O	N	8. TECH. OBJECTIVE % COMP.	e.	f.	g.
Program Plan and Test Plans High P_c																		43			
Low P_c																		100			
Monthly Reports																		63			
Quarterly Reports																		75			
Final Report Draft																		0			

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NASA APPROVED SCHEDULE

CONTRACTOR'S WORKING SCHEDULE

Task

XXI

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Lewis Research Center

CONTRACT PROGRESS SCHEDULE

REPORT FOR MONTH ENDING: 30 May, 1971

FORM APPROVED. BUDGET BUREAU NO. 104-R0007

9. NASA Use Only
a. NASA CODE
b. PROJECT MGR.
c. EVALUATION DATE
d. EXCEPTION CATEGORY

1. CONTRACT TITLE: Hydrogen-Oxygen APS Engines (High P_c)

2. CONTRACTOR (Name and address): Aerojet Liquid Rocket Co., P.O. Box 13222, Sacramento, California 95813

3. CONTRACT NO.: NAS 3-14354

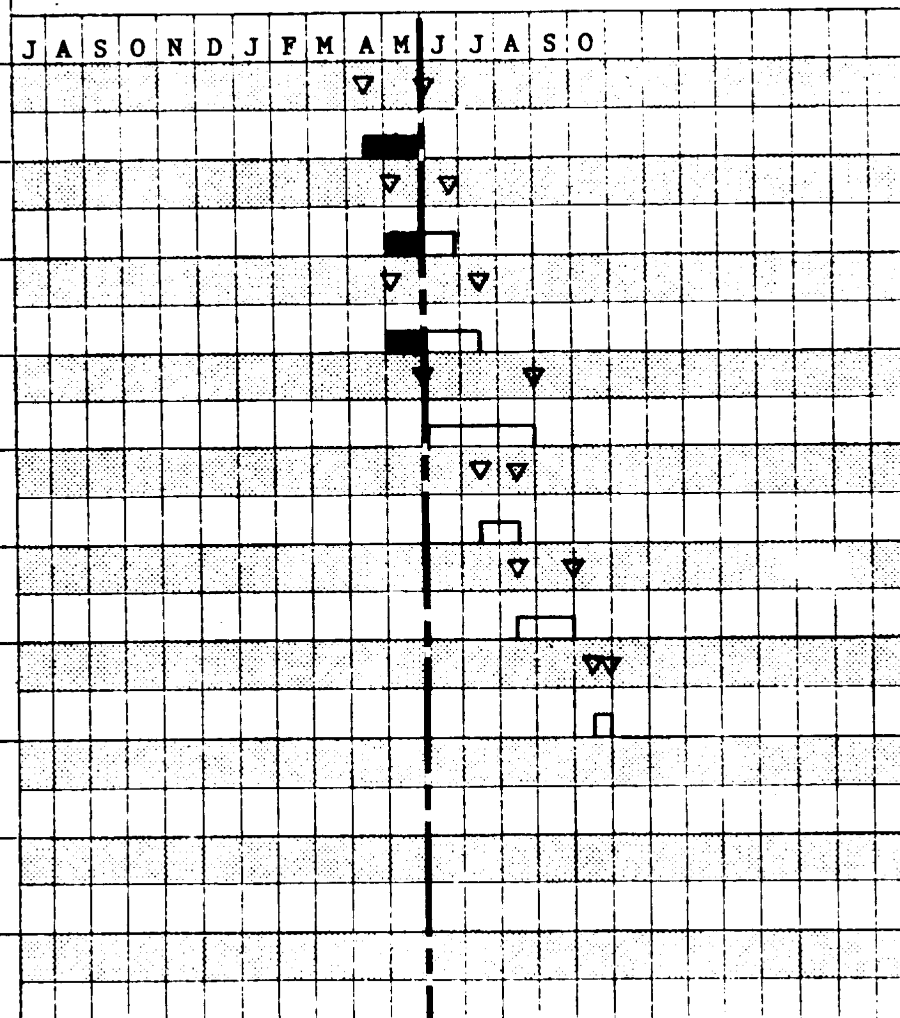
4. APPROVED (Contractor's Project Manager): L Schoenman

PREPARATION DATE: 6-10-71

5. NASA APPROVED SCHEDULE DATE:

Task	6. REPORTING CATEGORY For Low Temperature Propellants	8. TECH. OBJECTIVE % COMP.	e.	f.	g.
XXII	Injector Analysis & Design	85			
XXIII	Injector Fabrication	50			
XXIV	Thrust Chamber Analysis and Design	50			
XXV	Thrust Chamber Fabrication	5			
XXVI	Injector Checkout Tests	0			
XXVII	Cooled Chamber Tests	0			
XXVIII	Pulse Tests	0			

7.



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CONTRACTOR'S WORKING SCHEDULE